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REM REPORT NO AR-92-2R

IMPROVEMENT AND ANALYSIS OF THE RADIATION RESPONSE OF RADFET DOSIMETERS

FINAL TECHNICAL REPORT

CONTRACT NO: DAJA45-90-C-0042

by

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This is the Final Report on the preparation of three lots of improved RADFET dosimeter devices with the partial support U.S. Army Contract No. DAJA45-90-C-0042 and scientific collaboration from CECOM personnel visiting the UK, including radiation testing of RADFET samples. A silicon RADFET wafter fabrication run was made and tests of performance under irradiation were made, including a pulsed X-ray test as guests of the UK Ministry of Defence, correlated with tests on a Co-60 gamma therapy souce and copper tube X-rays. A new design of chip carrier was evaluated and found to be a useful advance in dosimeter packaging technique. The thickest oxide grown was 1.24 micro-meters. This had high responsivity and was very stable. The Army decided to have chips from these wafers packaged for the second and third deliveries.

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ABSTRACT

This is the Final Report on the preparation of three lots of improved RADFET dosimeters devices with the partial support of US Army Contract No. DAJA - 90 - C -0042 and scientific collaboration from US personnel visiting the UK, including intensive radiation testing of RADFET samples. A silicon RADFET wafer fabrication runs was made and tests of performance under irradiation were made, including a pulsed X-ray test as guests of the UK Ministry of Defence. This was correlated with tests on a Co-60 gamma therapy source. As well as the fabrication and testing of improved RADFET chips, a new dosimeter chip carrier was studied and found to be a useful advance in dosimeter packaging technique. In the groups of RADFETs delivered, the thickest oxide was 1.26 micrometres. This had high responsivity and was very stable. The Army decided to have chips from the same lot for the second and third deliveries.

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IMPROVEMENT AND ANALYSIS OF THE RADIATION RESPONSE OF RADFET DOSIMETERS

1. INTRODUCTION

This is the Final Report on the design, preparation and characterization of three lots of RADFET dosimeters devices with the partial support of US Army Contract No. DAJA - 90 - C -0042. A silicon RADFET wafer fabrication runs was made and tests of performance under irradiation were made. As well as the fabrication and testing of improved RADFET chips, a new dosimeter chip carrier was designed and found to be very useful by the US Army, CECOM, Fort Monmouth. The initial report on this contract was REM REPORT NO AR-90-1R, which was a Contract Plan; two Delivery Reports, AR-91-1R and AR-92-1R contained details of the three deliveries of devices under this contract. A scientific disacussion report AR-91-2R was also sent to our liaision scientists at Fort Monmouth. This gave a scientific review and an interpretation of some of the pulsed radiation test results obtained by the US Army at various times. The RADFET is a candidate for use in the AN/UDR-13 Pocket Radiac (Osman 1991).

The RADFET (Radiation-Sensitive Field Effect Transistor), dosimeter principle works on the buildup of space charge in the oxide film of a Metal - Oxide - Silicon structure, as shown in Fig. 1.1. The owner of REM was the originator of this method. Some references to subsequent work are given in Section 10, including work by Holmes-Siedle and Adams, August, Bechtel, Gentner and Kronenberg, East, Mc Gowan, Posey, Sarrabayrouse, Thomson and others cited in Section 10. Considerable success was reported in work supported by several agencies, including the US Army *. The objective was to improve the performance of the TOT500 design of RADFET in the "zero bias" mode, keeping the device layout and pinout the same but increasing the thickness of the radiation-sensitive oxide layer. The approach was to make fabrication run with an improved process specification and assess the performance under irradiation with zero gate bias and reconsider the absorber geometry around the chip. A novel chip carrier, developed by REM as an independent venture, was used as the packaging method for one delivery. The liaison scientists at CECOM have co-operated in the scientific work of the project.

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* A. Holmes - Siedle, "The Use of RADFETs in Radiation Dose Measurement", Final Technical Report, Contract DAJA45-87C-0029 (REM, Oxford, England, September 1989)

see also papers by Dr. S Kronenberg et al. in Section 10

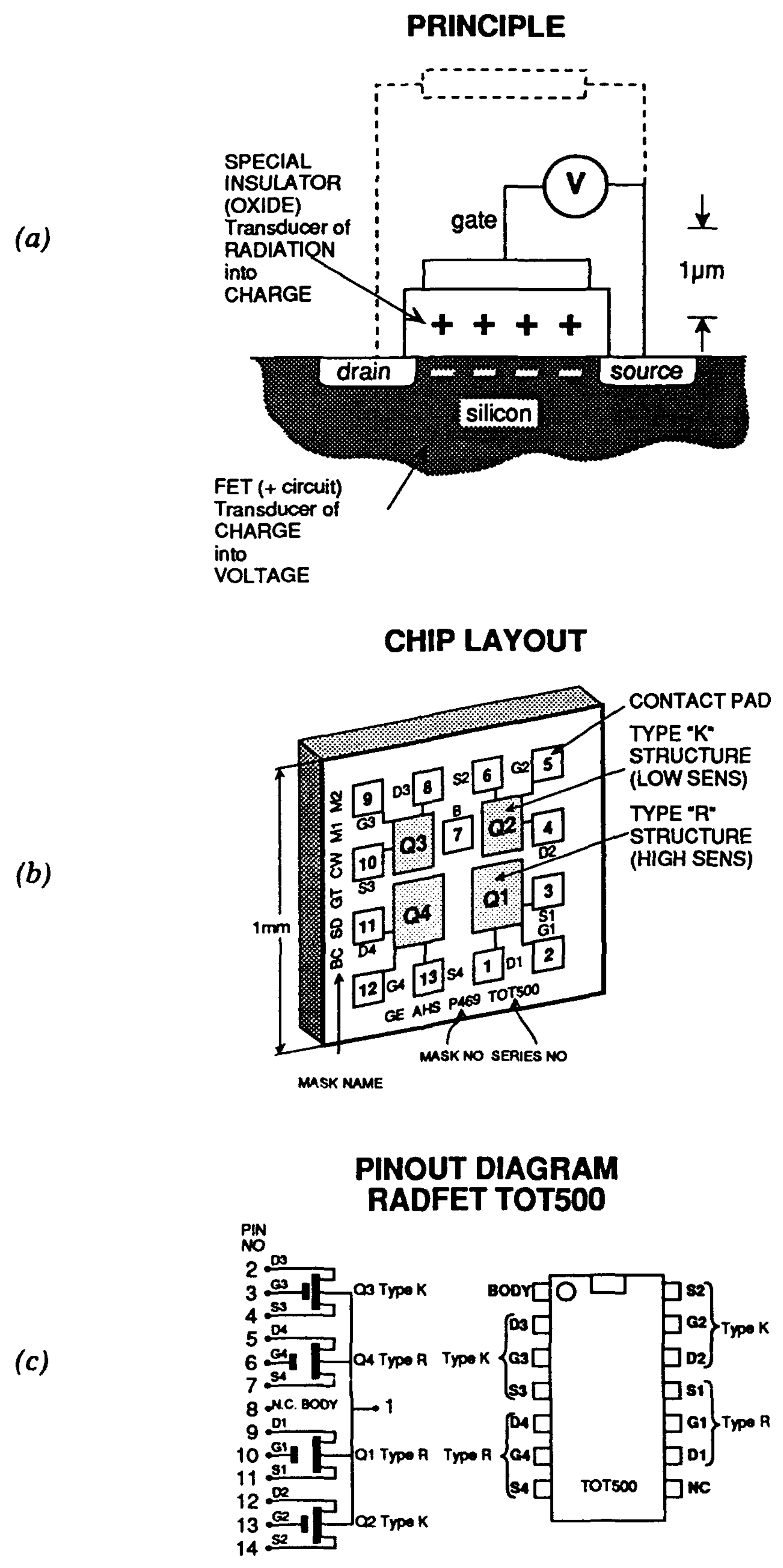


Fig. 1.1 Principle of a dosimetry system based on the RADFET (radiation-sensitive field effect transistor)

(a) Microscopic cross-section of chip

(b) Chip layout

(c) Circuit and pinout of FET's

2. New Wafer Process Run (SUMC No. P507U)

Fig. 1.1 shows the layout of REM's RADFET. It contains four specially designed field-effect transistors (FETs). All oxides are thicker than in normal FETs but two are extra thick (Type R, over 0.8 micrometres) and two are about three times a normal thickness (over 0.2 micrometres). All of REM's dosimeters are made at Southampton University Microelectronics Centre (SUMC) Over the past 15 years, REM and SUMC have developed a process for repeatable, high radiation sensitivity. For the 1990 run, the objectives included the exploration of improved zero-bias radiation response without change in stability. Although thicker oxides could be obtained by the use of deposition processes such as sputtering and chemical vapor deposition, it was decided that uniformity was not sufficiently good in these processes. It was decided to explore the maximum thermal oxidation period which could be withstood; the limits are determined mainly by undue spreading and dissipation of the source and drain junctions under the prolonged thermal stress at over 1000 degC. The source-drain spacing in the TOT500 mask is designed to allow for such effects.

Three different oxide thickness values were chosen, to cover the range from the existing process (Recipe 501, thickness 0.85 micrometres) to the maximum desired for this test (Recipe 504, goal 1.25 micrometres). Wafers 13 to 16 were to be of thickness 0.95 micrometres, two at 1,05 and two at 1.25. The oxide thickness goal for the Type K FETs was set to 0.12 micrometres on all wafers. This is thickness used in the earliest RADFETs, useful for high-dose work and it puts less thermal stress on the system than the previously used thickness for Type Ks, namely 0.25 micrometres. Other process steps such as anneals were modified, also in order to minimize the net thermal stress on the source-drain junctions.

As well as the above eight wafers run to REM's specifications, SUMC also included 12 further wafers, run at 0.95 μm to prove the scale on which RADFET wafers could be produced in their equipment (manufacturability) and study some new process modifications. These wafers may be used by REM in future studies. The oxide thicknesses were the same; oxidation ambients were varied. All 24 wafers in this run produced working RADFETs in high yield.

The wafer run, SUMC No. P507U, was carried out between November 1990 and January 1991. It proved to be a stable, well-behaved run of wafers. Measured oxide thickness values were 0.93, 1.06 and 1.26 micrometres for type R FETs and 0.13 micrometres for the Type K FETs.

It was considered by CECOM liaison scientists that the improvement of response gained in the above run was probably sufficient for the purposes of the project. There was also much work to do on the response and packaging of the new thick oxide devices. Therefore, a second process run, originally proposed, was not carried out and work was concentrated on device characterization and new package geometry.

3. Chip Mounting and Absorber Geometry

3.1. REM's New Chip Carrier, Type CC-3

3.1.2 General

Until recently, the standard RADFET package was a ceramic, 14-pin Dual-In-Line (DIL) design (width 8mm). During the period covered by the present contract, independent development by REM created an advanced, general-purpose package. This has novel features which will increase dosimetric accuracy. The outline of the package is shown in Fig. 3.1. The CC-3 Chip Carrier is polymeric (based on glass-epoxy board) and can be surface mounted or plugged into a probe head. It is designed to minimize radiation scattering and allow the fitting of a buildup cap over the chip. However, the pinout is 14 or 16 pin, as for the DIL. Dimensions are made so that, when a lead frame is added, it plugs straight into the existing 14-pin sockets of the RDR-100 reader. In quantity, it is anticipated that the cost of the carrier will be much lower than for normal DIL packages. This proprietary. development was used for the first delivery of the present contract.

The CC-3 epoxy chip carrier proved easy to handle. Dr. Stanley Kronenberg of CECOM and also the European Space Agency have worked with it and made positive comments. Although lighter, the device is easily picked out of sockets, has suffered no breakages and quickly equilibrates thermally.

3.1.3 Prospects for New Chip Carrier Technology

The supplier of the polymeric chip carrier technology will be available to make chip carriers in new geomwtries which may be needed for engineering models of the Pocket Radiac Project of EW/RSTA Center of CECOM. Smaller surface-mountable designs in this technology (e.g. a conventional SO-8 geometry) are already available and are being evaluated by REM.

3.2 Encapsulation

In the CC-3 carrier, the RADFET chip is usually encapsulated in a bead of silica-filled epoxy, although a lid can also be glued over the chip. The use of the filled epoxy is likely to give better secondary particle equilibrium than the air space in a DIL package and can also lower the cost per package.

Dr. Kronenberg of the US Army conducted experiments on adjustment of the filler composition in the epoxy coating and obtained a useful improvement in balance of front/back irradiation response. REM and its subcontractor decided to apply this atomic-weight-adjusted recipe to one production batch for CECOM.

REM's subcontractor used considerable production engineering skill in mixing and coating with encapsulant to which the special filler, specified by Fort Monmouth, had been added. The mixture

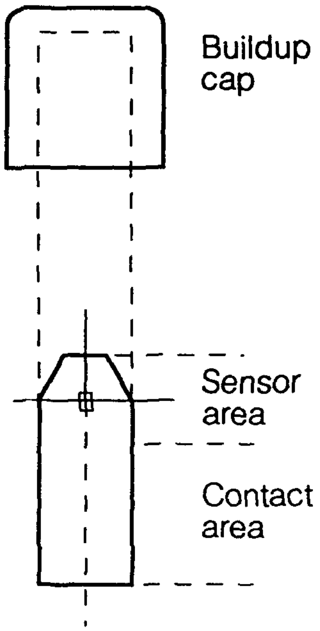


Fig 3.1 REM proprietary chip carrier Type CC-3. The contact system has 16 ways and can consist of an edge connector, dual-in-line pins, surface mountable pads or flying leads (e.g. cable wires). The buildup cap establishes electronic equilibrium in the silicon dioxide sensor system.

was much stiffer than normal and required stronger heating to form the usual "glob top". This gave a product with a light grey cap rather than the normal black. However, the number of rejects from this lot was much higher than normal (13 out of 73), possibly because of the extra forces put on the thin wires during encapsulation, which may have shorted or ruptured some of them. The extra heating required does not seem to have affected mechanical properties, FET stability or threshold voltage.

3.3 Buildup Material and Scattering From Packages

A problem identified by Army scientists in the conventional semiconductor packages (e.g. the ceramic Dual-in-Line, DIL) is the scattering from package material. These packages are not designed to minimize scattering. For example, the leads are thick kovar strip, plated with gold. Even though gold has been reduced in REM's current DIL header, the kovar leads cannot be altered. being fired in the ceramic. In addition, the chip is central in the package and it would be difficult to design a satisfactory buildup cap for correction of energy response.

For several applications, such as medical probes, REM is interested (a) in reducing the size of the package (b) in reducing the fortuitous heavy-metal scattering material; (c) making the application of a buildup cap to the chip more convenient. The first step in this process was the development of a proprietary design of chip carrier which still had the 14-pin geometry but fulfilled conditions (a) to (c) above. This is called the REM CC-3 carrier. Fig 3.1 shows the flexibility possibile with respect to the design of buildup caps. Details of the design are proprietary to REM. Stanley Kronenberg (CECOM) obtained some useful data on dosimeter response by putting a small silicon plate in place of the plastic lids used on experimental models, thus minimizing the non-uniformity of scattering materials around the sensitive region of the dosimeter. It would also be possible to design a "bare" dosimeter with very thin windows for low-energy photons (soft X-rays) or electrons (e.g. SEM beams).

3.4 Thinning

CECOM enquired about the possibility of producing RADFETs with silicon chip thickness values less than the 0.5 mm employed in standard 100-mm silicon wafers. At least two benefits may be obtained in this way (i) the reduction of photovoltages from the substrate (ii) the reduction of the diameter of miniature probes containg the RADFLΓ. REM studied the feasibility of producing thinned devices.

There are several approaches to thinner silicon : (a) obtain 100 mm or smaller blank silicon wafers having smaller thickness values and process in the normal way; (b) process 0.5 mm wafers as usual, then remove the back surface by lapping or etching; (c) the use of thin silicon films.

The reduction of photovoltages in MOS device substrates under pulsed radiation is normally achieved by use of thin-film (say 5 micrometre) silicon on insulating wafers of normal thickness. This achieves only objective (i) above and would require considerable research. Thus method (c) above was rejected.
The drawback with method (a) is that many wafers are broken if wafers of thickness lower than the standard are processed in the normal equipment. Investment in new equipment for handling such wafers would be needed and even then, a thickness reduction to 0.1 mm is the maximum that might be hoped for. This method was rejected for the present project. Method (b) is quite feasible, especially using lapping. However, whole wafers are needed. Considering the commercial value of a whole processed RADFET wafer as being in the region of $5 000, the development of a thinned process would probably require the investment of about $20,000. A more flexible back removal method is etching. This is ideally adapted to smaller areas and hence research can be performed with a smaller investment of processed wafer. It was thus decided to examine this method.

REM worked with BNF-Fulmer Microengineering center on the etching of dummy wafers with Hydrofluoric/Nitric/Acetic acid mixtures. The thickness target was 0.25 mm, thought to be the minimum at which the silicon could be sawn and the chips handled by assemblers. The front surface was protected with wax, the warm acid mixtures were agitated and various temperature-time recipes were tried. The back surfaces of the thinned wafers were measured with a "Talysurf" type mechanical surface profiler, accurate to about 1 micrometre. After about ten etch runs, it was concluded that it was feasible to control the end-point to say 0.25 mm plus/minus 10 percent. A difficulty which could not be overcome simply, however, was that the etching always had a characteristic edge-to-middle variation such that the etched region was dish-shaped. a variety of diferent methods of agitating and circulating the etchant was tried but none improved the flatness of the etched area. If the centre was of thickness 0.25, then the edges would in all cases be of thickness greater than 0.3 mm. Given a requirement of say 10 percent on the thickness of an individual 1 mm chip, then only the central area could be used, and the edges would be rejected as too thick. The very slight taper on each FET after sawing should not matter but yield from a wafer would be less than 30 percent. It was concluded that the method was feasible but wasteful.

Despite this, thinned parts of wafers were sent to REM's subcontractor for study with respect to the feasibility of:

- -hold-down during sawing
- -breakage during sawing
- -handling of chips with tweezers
- -surface tension due to the bead of liquid die bond adhesive before and during curing (could disturb the lighter chip)
- -damage during chip wire bonding.

The subcontractor reported that the above processes appeared to be feasible with a rejection rate about [illegible] percent above normal.

4. Electrical Measurements

4.1 General

In various sections, we will be comparing results for the "old" wafer runs of devices, mainly the TOT501C run of May 1989 (oxide thicknesses R: 0.86 ; K: 0.26 µm), with the "new", recipes designated 502,3 and 4 (oxide thiockness values of R being 0.95, 1.07 and 1.26 micrometres respectively, with all K devices being 0.13 micrometres) from Run P506U, described in Sec. 2.

4.2 Measurements at the wafer stage

The oxide thickness values were measured by SUMC by an optical method. The wafers were probed with the Suess automatic prober at SUMC using a jump distance of 4 mm (4 devices), over groups of 12 x 8 units in various parts of the wafer. The table below shows the measurements of typical threshold voltages, their spread, the maximum mismatch found between pairs of FETs and the drift up found when two readings of threshold voltage were taken, at 2 and 4 seconds after turnon.

Table 4.1. Values of threshold voltages taken by wafer probe REM RADFET wafer run No. P507U at SUMC

TOT No.	Wafer No.	doxR (µm)	doxK (µm)	VTR (V)	VTK (V)	Sprd (V)	Mism (V)	du (mV)
502A	14	0.94	0.13	7.9	2.6	0.15	0.07	1
	15	0.93	0.13	8.9	3.2	patchy		1
	16	0.93	0.13	7.9	2.9	0.58	0.05	1
503A	17	1.06	0.13	8.7	3.1	0.28	0.10	1
	18	1.07	0.13	8.2	3.1	0.71	0.10	1
504A	19	1.26	0.13	9.9	3.2	0.46	0.10	1
	20	1.24	0.13	11.0	3.4	0.48	0.10	1

doxR = oxide thickness of Type R device etc
VTR = threshold voltage of Type R device etc (at 10 µA)
sprd. = spread in 100 tabulated values of V(T)
mism. = the maximum pair mismatch in Type R values
du = drift up after reader turnon between 2 and 4 sec.

These tests show high stability and acceptable threshold voltage values. The threshold voltage of the thickest oxide is just under 10V for wafer 19. This is a success in limiting "fixed oxide charge", although the fact that the threshold value of wafer 20 shows 1V higher indicates that better threshold voltage control is still needed. The above data was used to select wafers

for initial sawing and assembly. Wafer 17 proved to give inoperative devices at the prototype stage so, for production lots, wafers 14, 18 and 19 were selected.

4.3 Electrical Measurement of Assembled RADFETs

4.3.1 Methods, General

The devices were measured with the Siltech RDR-100 reader. Threshold voltage values to 0.1 mV resolution were recorded using a computer logging system. This consisted of an intelligent digital voltmeter measuring the "Raw VT" output of the reader and connected by an RS232 link to a microcomputer running under MS-DOS. This software (PRODFET, see below) was demonstrated to Dr. Cohen in March 1992 and diskettes of this and a drift measuring program (STABFET) were passed to CECOM. The tables of device measurements given in this report were mainly prepared using the PRODFET routine.

The results show that the "drift up" (du) in threshold voltage value after "read" bias is switched on is normally very small before irradiation, being less than 1 mV between t = 2 and 4 sec (equivalent to about 3 mV per decade of time). The drift is due to the emptying of a few "slow interface states" caused during oxide growth, as they respond to the change in oxide field when a negative voltage of magnitude V(T) is applied to the gate. This is insignificant compared with the values of drift which occur AFTER irradiation to more than 100 rads. However, making automated measurement at two intervals catches another form of behavior, namely "jumpiness" of V(T), caused by an unstable I-V characteristic, instantly recognizable by the amplitude of du(2-4 sec), which may be +/- 100 mV. The du value also acts as an informal monitor of the "quality" of the as-grown interface.

4.3.2 PRODFET program

The PRODFET program in QuickBasic was used to store the values for VT at 2 and 4 seconds after application of "read" bias to each device. Switching of the RDR-100 was done manually after a signal from the computer instructed the operator to turn on the "read" bias" for Q4, 1,2 and 3 in turn. Table 4.1 gives an example of the printout of data taken by the PRODFET routine. The figure under "Q42s" if the threshold voltage a 40 microamps, taken 2 seconds after the RDR-100 reader is switched to Q4. The column marked "4s" is the drift observed when the same measurement is repeated 2 seconds later. This is the quantity normally given the symbol "du", i.e. the "drift up" of the VT value between readings at 2 and 4 seconds after switchon. True values of du are probably smaller than those shown, as we will now explain. To ensure full thermal equilibration of the chips after insertion into the socket would have taken an inordinate time. Some of the drift recorded is thermal drift and not due to charge drift in the oxide or interface. A smaller reading was always obtained if the device was left for a while to equilibrate thermally before measurements.

Table 4.2

ELECTRICAL MEASUREMENTS ON RADFETS DELIVERED

AS ITEMS 0001AB AND AC OF CONTRACT DAJA-C90-0042

Computer files of data, tabulated by spreadsheet

KEY TO SYMBOLS

"Q1 2s" is reading 2 sec after "read" current at 40 microamps is switched to FET no. Q1

"4s" is the change in the reading on Q1 2 seconds later

"90µA" is the change in the reading on Q1 after raising the read current to 90 microamps (a measure of the gain)

100% MEASUREMENT OF PRODUCTION BATCH, PRODFET ROUTINE
100% sampling from 1-35 ; file P14-1
LOT TOT502A-14-5   29 March 1992

Device	Time	Q4 2s	4s	90uA	Q1 2s	4s	90uA	Q2 2s	4s	90uA	Q3 2s	4s	90uA
1	2047	7.9327 1	0.2 1	582 1	8.3985 1	0.3 1	654 1	2.6220 1	-0.1 1	287 1	0.0000 1	0.0 1	999 1
2	2049	8.0475 1	0.5 1	583 1	8.0898 1	0.6 1	584 1	3.3796 1	0.5 1	694 1	2.6354 1	0.0 1	282 1
3	2050	8.1953 1	0.3 1	600 1	8.0580 1	0.9 1	591 1	2.5000 1	0.5 1	295 1	2.5814 1	2.9 1	253 1
4	2051	8.0614 1	0.5 1	582 1	8.1011 1	0.5 1	584 1	2.6217 1	-0.4 1	284 1	2.5979 1	0.0 1	282 1
5	2053	8.1603 1	0.3 1	587 1	8.3064 1	0.9 1	615 1	2.6353 1	0.1 1	283 1	0.9397 1	0.5 1	295 1
6	2055	8.0636 1	0.7 1	592 1	8.1821 1	0.5 1	599 1	2.6543 1	-0.4 1	290 1	2.6095 1	0.0 1	286 1
7	2057	8.0256 1	0.2 1	585 1	8.0495 1	0.2 1	584 1	2.6314 1	0.2 1	265 1	2.5397 1	0.5 1	320 1
8	2058	8.0251 1	0.5 1	577 1	8.0311 1	0.5 1	586 1	2.6222 1	-0.2 1	281 1	2.4286 1	0.5 1	270 1
9	2059	7.9828 1	0.3 1	574 1	8.1189 1	0.5 1	587 1	2.6444 1	-0.1 1	286 1	2.6389 1	-0.1 1	283 1
10	2100	8.0099 1	0.1 1	586 1	7.9110 1	0.0 1	578 1	2.5861 1	-0.5 1	283 1	2.5923 1	0.0 1	285 1
11	2102	8.0662 1	0.7 1	602 1	8.2026 1	0.3 1	609 1	2.6114 1	0.0 1	290 1	2.5543 1	0.3 1	288 1
12	2103	8.0385 1	0.3 1	580 1	8.1946 1	0.1 1	600 1	2.6125 1	-0.1 1	263 1	2.6557 1	0.0 1	284 1
13	2105	8.0281 1	0.4 1	589 1	8.1600 1	0.3 1	643 1	2.5748 1	0.5 1	267 1	2.6320 1	-0.2 1	286 1
14	2106	7.9670 1	0.3 1	573 1	8.0148 1	0.5 1	574 1	2.6154 1	0.0 1	282 1	2.6115 1	0.3 1	280 1
15	2108	8.0568 1	0.3 1	592 1	8.1549 1	0.6 1	656 1	2.5988 1	-0.6 1	285 1	2.5924 1	0.0 1	286 1
16	2109	8.1333 1	0.4 1	600 1	8.2514 1	0.3 1	644 1	4.7062 1	58.7 1	991 1	2.6306 1	0.2 1	287 1
17	2110	7.9614 1	0.5 1	599 1	8.0540 1	0.5 1	615 1	2.6443 1	-0.1 1	292 1	2.5320 1	3.1 1	232 1
18	2112	7.8134 1	0.1 1	575 1	7.9675 1	0.2 1	585 1	2.6150 1	-0.8 1	285 1	2.4894 1	7.8 1	295 1
19	1425	8.0546 1	0.3 1	613 1	8.2833 1	0.2 1	637 1	2.5265 1	-0.1 1	289 1	2.5448 1	1.8 1	270 1
20	1426	7.8990 1	0.4 1	595 1	8.1192 1	0.7 1	644 1	2.5999 1	0.0 1	292 1	2.5271 1	-0.8 1	282 1
21	1427	8.0141 1	0.2 1	605 1	8.1277 1	0.2 1	623 1	2.5729 1	1.1 1	256 1	2.6374 1	0.0 1	293 1
22	1428	7.9189 1	0.2 1	599 1	8.0184 1	0.4 1	606 1	2.5527 1	3.1 1	307 1	2.5574 1	-0.4 1	284 1
23	1429	8.1521 1	0.4 1	616 1	7.9841 1	0.4 1	602 1	2.5927 1	0.1 1	289 1	2.6434 1	0.3 1	297 1
24	1430	8.0770 1	0.2 1	597 1	8.0587 1	0.8 1	593 1	2.6277 1	-0.1 1	288 1	2.5902 1	0.5 1	297 1
25	1431	8.0674 1	0.4 1	609 1	8.0860 1	0.8 1	612 1	2.5777 1	1.0 1	290 1	2.6285 1	0.0 1	291 1
26	1432	7.9981 1	0.2 1	611 1	8.0013 1	0.6 1	611 1	2.6248 1	0.5 1	285 1	2.5998 1	0.2 1	294 1
27	1434	8.1139 1	0.3 1	611 1	8.1041 1	0.5 1	606 1	2.6234 1	0.0 1	261 1	2.6332 1	0.1 1	294 1
28	1434	7.9397 1	0.4 1	586 1	8.1351 1	0.5 1	614 1	2.6209 1	0.0 1	288 1	2.6046 1	0.2 1	287 1
29	1436	8.2983 1	0.4 1	665 1	8.6104 1	0.5 1	701 1	2.7162 1	-0.1 1	315 1	2.5000 1	0.5 1	295 1
30	1437	7.9140 1	0.4 1	603 1	8.0606 1	0.7 1	622 1	2.6744 1	0.5 1	300 1	2.5758 1	-0.1 1	296 1
31	1438	7.9414 1	0.6 1	610 1	7.9738 1	0.6 1	619 1	2.6179 1	-0.1 1	297 1	2.5983 1	-0.4 1	297 1
32	1439	7.9176 1	0.6 1	591 1	8.1217 1	0.8 1	618 1	2.6591 1	-0.4 1	290 1	2.5000 1	0.5 1	295 1
33	1441	7.9322 1	0.4 1	601 1	8.0323 1	0.4 1	638 1	2.5849 1	0.6 1	284 1	2.6229 1	0.0 1	293 1
34	1442	8.0186 1	0.4 1	609 1	7.9410 1	0.8 1	613 1	2.5782 1	-0.1 1	292 1	2.5926 1	0.5 1	295 1
35	1442	7.9258 1	0.3 1	600 1	8.1560 1	0.9 1	620 1	2.6296 1	0.0 1	294 1	2.5000 1	0.5 1	295 1
35	1446	7.9281 1	0.3 1	599 1	8.1599 1	0.2 1	618 1	2.6302 1	-0.1 1	294 1	2.5959 1	1.7 1	291 1

PRODUCTION LOT OF RADFETS - 100% PRODFET MEASUREMENT.
100% sampling from 1-90; 1 in 5 from 91-120
Files P19-1 and 2, 29/3/92 & 1/4/92 (p19-n.wks)
Lot TOT504A-19-6

Device	Time	Q4 2s	4s	90uA	Q1 2s	4s	90uA	Q2 2s	4s	90uA	Q3 2s	4s	90uA	Comment
1	2140	10.1185 1	0.5 1	559 1	10.3102 1	0.7 1	584 1	3.2254 1	0.1 1	257 1	3.1953 1	0.0 1	255 1	19.3C
2	2145	10.2526 1	0.3 1	559 1	10.2314 1	0.4 1	557 1	3.1740 1	0.2 1	251 1	3.2391 1	0.0 1	257 1	
3	2153	9.9107 1	0.2 1	541 1	9.9779 1	0.3 1	541 1	3.1454 1	0.2 1	248 1	3.0879 1	0.5 1	246 1	19.2C
4	2244	10.2835 1	0.3 1	563 1	10.2378 1	0.1 1	560 1	3.2293 1	0.3 1	258 1	3.2026 1	0.1 1	255 1	
5	2248	9.7718 1	0.3 1	524 1	9.7151 1	0.3 1	520 1	3.1115 1	0.2 1	249 1	3.1694 1	0.5 1	245 1	
6	2250	10.0542 1	0.6 1	546 1	9.9873 1	0.7 1	540 1	3.1504 1	0.3 1	249 1	3.1695 1	0.2 1	257 1	20C
7	2252	10.2464 1	0.2 1	559 1	10.2141 1	0.5 1	557 1	3.2547 1	0.4 1	257 1	3.1623 1	0.1 1	264 1	
8	1504	10.0551 1	0.5 1	554 1	10.2301 1	1.0 1	562 1	3.2409 1	0.1 1	261 1	3.1166 1	8.4 1	299 1	
9	1505	9.8759 1	0.5 1	532 1	9.9318 1	0.5 1	535 1	3.1918 1	0.2 1	251 1	3.0922 1	0.5 1	242 1	
10	1507	10.1867 1	0.5 1	544 1	10.1498 1	0.5 1	542 1	3.2333 1	0.2 1	252 1	3.2393 1	0.2 1	295 1	
11	1511	10.7484 1	0.0 1	586 1	10.4317 1	0.2 1	562 1	3.2537 1	0.5 1	250 1	3.2085 1	0.4 1	253 1	19.8
12	1513	9.8568 1	0.2 1	519 1	9.9478 1	0.2 1	522 1	3.1801 1	0.1 1	295 1	3.1654 1	0.3 1	246 1	
13	1516	10.0053 1	0.2 1	531 1	9.8439 1	0.0 1	524 1	3.1991 1	0.3 1	251 1	3.2216 1	0.3 1	253 1	
13	1517	9.9620 1	0.4 1	524 1	9.9172 1	0.7 1	519 1	3.1447 1	1.8 1	244 1	3.1946 1	0.5 1	290 1	
15	1519	10.0364 1	0.6 1	561 1	10.0323 1	0.2 1	552 1	3.1592 1	0.4 1	257 1	3.1267 1	0.2 1	290 1	
16	1529	10.1682 1	0.3 1	558 1	10.1539 1	0.4 1	560 1	3.2038 1	0.1 1	252 1	3.1966 1	1.0 1	290 1	21.4
17	1532	10.3066 1	0.4 1	561 1	10.4068 1	0.2 1	567 1	3.2580 1	0.2 1	257 1	3.2042 1	1.0 1	290 1	
18	1534	10.0775 1	0.4 1	546 1	10.2183 1	0.4 1	554 1	3.2231 1	0.0 1	253 1	3.2595 1	0.1 1	257 1	
19	1536	10.2002 1	0.3 1	561 1	10.2423 1	0.3 1	565 1	3.2398 1	0.3 1	257 1	3.1876 1	0.5 1	290 1	
20	1537	10.0270 1	0.5 1	555 1	10.0095 1	0.9 1	551 1	3.1800 1	0.7 1	250 1	3.2113 1	0.1 1	259 1	
21	1539	9.9855 1	0.7 1	538 1	9.7118 1	0.3 1	529 1	3.1505 1	0.1 1	250 1	4.0750 1	0.5 1	290 1	
22	1540	10.0238 1	0.2 1	544 1	10.0797 1	0.4 1	548 1	3.1193 1	1.5 1	261 1	3.5000 1	0.5 1	250 1	
23	1542	9.6437 1	0.4 1	512 1	9.8182 1	1.1 1	530 1	3.1533 1	0.0 1	248 1	3.1094 1	0.5 1	251 1	
24	1544	10.1124 1	0.2 1	562 1	10.2878 1	0.5 1	571 1	3.1968 1	0.6 1	262 1	3.1354 1	1.3 1	255 1	21.7
25	1545	10.3048 1	0.2 1	568 1	10.3238 1	0.4 1	573 1	3.2152 1	0.9 1	261 1	3.2061 1	0.5 1	290 1	21.7
30	1547	9.4422 1	0.5 1	489 1	9.3007 1	0.6 1	479 1	3.0622 1	0.2 1	223 1	3.0211 1	0.5 1	224 1	
27	1548	9.5172 1	0.4 1	479 1	9.4607 1	0.6 1	483 1	3.1521 1	0.4 1	250 1	3.0460 1	0.8 1	227 1	
28	1550	9.6643 1	0.1 1	505 1	9.8977 1	0.5 1	526 1	3.1521 1	0.1 1	246 1	3.1184 1	0.3 1	240 1	
29	1551	9.7911 1	0.2 1	516 1	9.6760 1	0.3 1	510 1	3.0750 1	0.8 1	242 1	3.0610 1	0.2 1	239 1	
30	1554	9.8728 1	0.3 1	523 1	9.8583 1	0.4 1	520 1	3.1335 1	0.5 1	250 1	3.0952 1	4.3 1	238 1	21.7
31	1719	9.8624 1	0.4 1	504 1	9.5517 1	0.5 1	492 1	3.0625 1	1.2 1	204 1	3.1256 1	0.3 1	241 1	
32	1720	10.4092 1	0.4 1	555 1	9.9584 1	0.4 1	537 1	3.1933 1	0.0 1	246 1	3.1900 1	0.1 1	244 1	22.8
33	1721	9.2569 1	0.3 1	451 1	5.3305 1	9.9 1	352 1	2.9811 1	0.6 1	247 1	3.0420 1	0.2 1	226 1	
34	1723	9.3472 1	0.6 1	476 1	9.0433 1	0.2 1	463 1	3.0555 1	0.2 1	229 1	3.0411 1	0.5 1	222 1	
35	1727	9.9999 1	0.0 1	999 1	9.7850 1	0.6 1	518 1	3.0639 1	0.3 1	242 1	3.0933 1	0.2 1	235 1	23.3
36	1728	9.9172 1	0.6 1	521 1	9.8869 1	0.7 1	521 1	3.1638 1	0.1 1	241 1	3.1099 1	0.1 1	234 1	
37	1730	9.6832 1	0.6 1	509 1	9.7645 1	0.2 1	516 1	3.0809 1	0.2 1	234 1	3.1070 1	0.5 1	250 1	
38	1731	10.0205 1	0.5 1	519 1	10.1116 1	0.8 1	541 1	3.1994 1	0.0 1	248 1	3.1885 1	0.1 1	246 1	23.2
38	1732	9.4049 1	0.4 1	491 1	9.5636 1	0.5 1	504 1	3.0619 1	0.4 1	229 1	3.0656 1	0.1 1	234 1	
40	1733	9.4894 1	0.3 1	489 1	9.6514 1	0.5 1	504 1	3.1203 1	0.7 1	250 1	0.0000 1	0.5 1	250 1	
41	1735	9.8907 1	0.5 1	526 1	9.8055 1	0.5 1	523 1	3.1704 1	0.5 1	250 1	3.1749 1	0.0 1	248 1	23.8
42	1737	9.9011 1	0.4 1	522 1	5.2553 1	0.5 1	65 1	3.1342 1	0.6 1	249 1	3.1863 1	0.1 1	249 1	
43	1740	9.5494 1	0.4 1	479 1	9.8281 1	0.7 1	514 1	3.1555 1	0.0 1	243 1	3.1219 1	0.3 1	235 1	23.1
44	1742	9.9507 1	0.6 1	549 1	9.8006 1	0.5 1	540 1	3.3333 1	0.5 1	250 1	3.1806 1	0.3 1	256 1	24
45	1744	10.1376 1	0.3 1	557 1	10.1280 1	0.4 1	554 1	3.2270 1	0.2 1	255 1	3.1459 1	4.9 1	260 1	

46	1746	10.0429	1	0.3	1	526	1	9.6813	1	0.4	1	510	1	3.1144	1	0.2	1	240	1	3.1044	1	0.5	1	242	1	
47	1748	10.1342	1	0.5	1	548	1	10.3768	1	0.7	1	555	1	3.1404	1	1.3	1	250	1	3.1229	1	0.4	1	236	1	22.1
48	1749	9.3005	1	0.4	1	490	1	9.5474	1	0.5	1	503	1	3.0973	1	0.5	1	250	1	3.0820	1	0.1	1	233	1	
49	1751	10.3167	1	0.6	1	553	1	10.3370	1	0.5	1	558	1	3.1711	1	0.4	1	252	1	3.1843	1	0.3	1	246	1	
50	1752	9.5861	1	0.3	1	503	1	9.7117	1	1.1	1	511	1	3.1186	1	0.2	1	237	1	3.1171	1	0.3	1	250	1	
51	1758	10.5733	1	0.6	1	589	1	10.3135	1	0.8	1	580	1	3.2239	1	2.6	1	197	1	3.2458	1	0.5	1	260	1	
52	1800	10.2337	1	1.0	1	571	1	10.1763	1	0.7	1	568	1	3.1899	1	0.1	1	252	1	3.1693	1	5.0	1	260	1	
53	1801	9.7046	1	0.4	1	526	1	9.8485	1	0.8	1	535	1	3.1743	1	0.0	1	250	1	3.1699	1	2.4	1	257	1	
54	1802	10.2267	1	0.5	1	575	1	10.2347	1	0.4	1	576	1	0.0615	1	0.4	1	250	1	3.2308	1	0.3	1	262	1	
55	1804	10.1979	1	0.4	1	564	1	9.7291	1	0.5	1	527	1	3.1444	1	0.9	1	249	1	3.1605	1	0.3	1	257	1	
56	1805	10.2266	1	0.3	1	571	1	10.2441	1	0.1	1	572	1	3.2404	1	0.5	1	258	1	2.9719	1	0.5	1	311	1	
57	1806	9.9323	1	0.5	1	538	1	9.9558	1	0.6	1	540	1	3.2181	1	0.5	1	103	1	3.1731	1	0.8	1	250	1	
58	1808	10.1201	1	0.3	1	557	1	10.1791	1	0.6	1	558	1	3.2348	1	0.3	1	258	1	1.8872	1	9.9	1	450	1	
59	1809	10.4324	1	0.5	1	577	1	10.4360	1	0.6	1	577	1	3.2751	1	0.2	1	261	1	3.1918	1	0.0	1	263	1	
60	1810	9.9593	1	0.4	1	551	1	9.9472	1	0.5	1	550	1	3.2118	1	0.2	1	257	1	3.1886	1	0.2	1	254	1	
61	1935	10.0857	1	1.0	1	558	1	10.0411	1	0.9	1	553	1	3.2183	1	0.2	1	257	1	3.2185	1	0.3	1	782	1	
62	1936	10.6912	1	1.0	1	595	1	10.7474	1	0.9	1	597	1	3.3333	1	0.5	1	250	1	3.2308	1	0.6	1	266	1	
63	1937	10.1801	1	1.0	1	564	1	10.2025	1	0.8	1	564	1	3.2448	1	0.2	1	260	1	3.1921	1	0.3	1	260	1	
64	1938	10.3704	1	0.5	1	564	1	10.3766	1	0.6	1	568	1	3.2617	1	0.1	1	257	1	3.2404	1	0.5	1	251	1	
65	1939	10.2414	1	0.5	1	559	1	10.3112	1	0.7	1	571	1	3.2232	1	0.5	1	258	1	3.2027	1	0.2	1	247	1	
66	1940	10.2182	1	0.6	1	564	1	10.2172	1	0.5	1	563	1	3.2545	1	0.2	1	261	1	3.2479	1	0.2	1	262	1	
67	1941	10.1554	1	0.4	1	547	1	10.1780	1	0.1	1	558	1	3.2319	1	0.2	1	250	1	3.2301	1	0.4	1	253	1	
68	1943	9.8554	1	0.6	1	541	1	9.8527	1	0.6	1	539	1	3.1824	1	0.1	1	255	1	3.2045	1	0.5	1	250	1	
69	1945	10.0930	1	0.3	1	553	1	10.0365	1	0.3	1	547	1	3.2257	1	0.2	1	250	1	3.2053	1	0.2	1	258	1	
70	1946	10.1215	1	0.5	1	557	1	10.1605	1	0.6	1	561	1	3.2171	1	2.0	1	250	1	3.2202	1	0.2	1	258	1	
71	1948	10.3490	1	0.2	1	563	1	10.3321	1	0.6	1	564	1	3.2077	1	0.5	1	250	1	3.2569	1	0.3	1	259	1	
72	1950	9.9606	1	0.5	1	544	1	10.1110	1	0.3	1	554	1	5.5398	1	0.5	1	250	1	3.1181	1	0.1	1	248	1	
73	1952	9.6604	1	0.4	1	525	1	9.9672	1	0.9	1	567	1	3.1692	1	0.5	1	831	1	3.1905	1	0.3	1	255	1	
74	1953	9.8603	1	0.0	1	538	1	9.8107	1	0.6	1	536	1	3.1704	1	0.5	1	253	1	3.1876	1	0.1	1	253	1	
75	1955	10.0369	1	0.4	1	550	1	10.4496	1	0.7	1	579	1	9.6196	1	0.5	1	368	1	3.1800	1	0.2	1	255	1	
76	1956	9.9544	1	0.3	1	533	1	9.9586	1	0.3	1	532	1	3.2206	1	0.0	1	250	1	3.1030	1	1.7	1	241	1	
77	1958	10.2596	1	0.4	1	565	1	10.2624	1	0.1	1	564	1	3.2502	1	0.1	1	260	1	3.2065	1	0.7	1	262	1	
78	1959	10.3282	1	0.2	1	560	1	10.3059	1	0.5	1	557	1	3.2590	1	0.3	1	257	1	3.2675	1	0.4	1	260	1	
79	2000	0.0000	1	0.0	1	0	1	10.2112	1	0.4	1	565	1	3.2380	1	0.2	1	260	1	5.4717	1	9.9	1	176	1	
80	2003	10.1084	1	0.4	1	545	1	10.1754	1	0.4	1	547	1	3.2278	1	0.0	1	253	1	3.1913	1	0.2	1	249	1	
81	2004	10.2139	1	0.3	1	562	1	10.2829	1	0.4	1	566	1	3.2575	1	0.1	1	260	1	3.2307	1	0.4	1	256	1	
82	2006	9.9385	1	0.6	1	548	1	9.8918	1	0.7	1	547	1	3.2118	1	0.1	1	255	1	3.1812	1	0.1	1	255	1	
83	2008	9.8276	1	0.4	1	534	1	9.7351	1	0.9	1	535	1	3.1863	1	0.0	1	253	1	3.1691	1	0.3	1	256	1	
84	2009	10.0843	1	0.4	1	553	1	10.0883	1	0.7	1	555	1	3.2125	1	0.2	1	257	1	3.1688	1	0.5	1	252	1	
86	2013	10.4583	1	0.8	1	572	1	10.3928	1	0.9	1	563	1	3.2137	1	0.2	1	257	1	3.2424	1	0.5	1	256	1	
87	2013	10.0310	1	0.6	1	535	1	10.0432	1	0.7	1	537	1	3.1911	1	0.2	1	248	1	3.5492	1	0.5	1	261	1	
88	2015	10.0192	1	0.3	1	536	1	10.1469	1	0.3	1	548	1	3.2345	1	0.2	1	253	1	3.1904	1	0.3	1	250	1	
89	1628	9.4528	1	0.5	1	526	1	9.4678	1	0.8	1	528	1	3.1130	1	0.6	1	249	1	3.1359	1	0.3	1	252	1	
90	1629	10.0121	1	0.5	1	556	1	10.1065	1	0.5	1	558	1	3.1876	1	0.8	1	256	1	3.1837	1	0.7	1	253	1	
sampling every 5																										
95	1631	10.1917	1	0.6	1	556	1	10.2005	1	0.8	1	560	1	3.1961	1	0.7	1	249	1	3.0961	1	0.9	1	263	1	sampling
100	1632	10.1603	1	0.5	1	563	1	10.2864	1	0.4	1	569	1	3.2293	1	0.1	1	259	1	5.0000	1	0.5	1	250	1	
105	1637	10.3523	1	0.4	1	576	1	10.3875	1	0.3	1	578	1	3.2685	1	0.2	1	262	1	3.1901	1	1.5	1	260	1	
110	1638	10.2434	1	0.3	1	573	1	10.2470	1	0.6	1	572	1	3.2543	1	0.2	1	263	1	3.2556	1	0.1	1	250	1	
115	1640	10.0195	1	0.3	1	555	1	10.1675	1	0.6	1	570	1	3.1795	1	0.0	1	250	1	3.1319	1	3.0	1	261	1	
120	1641	9.8698	1	0.4	1	546	1	10.1578	1	0.1	1	592	1	3.2113	1	1.0	1	265	1	3.1542	1	0.2	1	250	1	last

The next column in Table 4.1, named "90uA" is the difference in reader voltages obtained when switching the current from 40 to 90 microamperes. This is the term we often refer to as "diff" and is inversely proportional to the transconductance of the FET. In the present measurements, it serves as a useful check that the I(D) - V(G) characteristic is normal and uniform across a wafer.

Some examples of the screen display given by PRODFET are shown in Appendix A. The data was used for the selection of some prototype devices for a NATO cross-comparison test. The data, stored as ASCII files under MS-DOS, are formatted for use in spreadsheets.

4.3.3 STABFET Program

This program is to obtain a picture of the stability of threshold voltages of RADFETs over long periods of time. It is simply a program which records the threshold voltage reading at set times and displays as well the drift values for chosen intervals such as a decade of time and some twofold time increments. The data has confirmed that the threshold voltage drift is a logarithmic function of time over several decades of time. This lends confidence that the drift phenomena noted will die out with time and will not produce large drift errors in a Pocket Radiac arrangement. Some examples of the screen display given by PRODFET are shown in Appendix A. The data, stored as ASCII files under MS-DOS, are formatted for use in spreadsheets.

4.3.4 Rating system

There are four independent RADFET elements on each RADFET chip (Q1 and Q4 are thick oxide; Q2 and Q3 are thin oxide. Devices with even one element working can be used for testing. Our classification of operability includes A (four working) ; A' (one bad, three working); A'' (two bad) and so on. Stability ratings are less simply defined but include Ag (Acceptable, good) and Ae (acceptable, excellent) (see Section on Electrical Measurements. The usual "drift up" (du) in threshold voltage value after the "read" bias is switched on is normally very small before irradiation. The target in the present project was not to have drift up values larger than in previous devices.

As stated in earlier reports, the thin oxide device is not seen as being useful at present in the CECOM program. Therefore grade A' with the Type K devices inoperative is "as good as a Grade A".

Devices which had one of four FETs inoperative due to short, open circuit or poor I-V characteristic are graded A'. Those which have very large values of du are classified Rdu.Small values of drift and values of VT within the normal distribution confer the grade [A] for "Acceptable". The previous report gave a goal for the delivery of not more than 20 percent of Grade A' or worse.

In Section 6 we list the spread of threshold voltages, typical values of drift and numbers of "Rejects" i.e. of low-graded devices. Lot 1AA, the first delivery, used the CC-3 Chip Carrier. The highest number of low-graded devices occurs in sublot

504A-19-2, the lot with "special filler". In addition to the 14 shown (electrical faults in one of 4 devices), 6 were rejected in the factory for faults of unknown type. The inoperative device is always one of the thin oxide FETs, which is not used in the US Army's applications. In most of the other sublots, the number of devices in the A category were more than adequate. Therefore, the percentage overall of devices below grade A is well within the limits proposed. For Lots 1AB and 1AC, the yield was even higher.

The most likely cause of low yield in the specially filled lot is that the stiffness of the unconventional formula of epoxy encapsulant laid extra strain on the thin Al bonding wires and caused shorts or open-circuits.

4.4 Electrical Measurements - Results

In Section 6, the distributions of VT, du and diff values within a batch are seen to be quite uniform. For wafer 19, the values vary from 9.3 to 10.3 for the Type R and 3.0 to 3.3 for Type K. The distributions and values are similar to those measured by wafer probe. Thus there is no gross effect of encapsulation.

One indication that the wafer run had been successful is that V(T) values were low. For example, for even the thickest oxide, V(T) was below 10V for 90 percent of the samples assembled from wafer 19 (thickness 1.24 micormetres), a typical value being 9.5V. The "diff" value ((V(T) for 40 vs 90 μA) was about 500 mV. Equivalent figures for the 0.85 μm chips were 8.5 V and 300 mV respectively.

5. Radiation Response

5.1 General

REM and collaborators, especially the European Space Agency, has exposed RADFETs to many different types of particle (Holmes-Siedle et al, se refs in Section 10). CECOM has made comparative tests of REM's and competing RADFETs (see. e.g. Bechtel, Gentner and Kronenberg, 1991). Figure 5.1 shows REM's published calibration curves.

5.2 Growth Curves

5.2.1 Linear and Non- Linear

A calibration curve plotting threshold voltage shift versus dose is often called a Growth Curve, since it is caused by the growth of charge in the oxide. An important advantage of irradiation under positive bias is that the growth curve is very nearly linear. The important practical disadvantage of the positive-bias mode is that the reading is compromized if gate voltage is interrupted for more than a short period.

The zero-bias V(I)0 mode has the advantage that dosimeters can be exposed while detached from the reader. The charge in the oxides is also less likely to fade if no field stress is applied during the long times over which exposure may occur. The main disadvantage of the zero-bias mode is that the growth of delta V(T) per unit dose increment "rolls off" at higher dose values, that is the growth vs. dose becomes non-linear. This is to be expected because there is no driving gate field to overcome increasing internal fields (see e.g. Holmes-Siedle 1986). Appendix B contain typical commercial specifications for TOT500 devices, including the zero-bias and +20V bias versions of growth curves, one of which is reproduced as Fig.5.1. The "rolloff" is expressed here as a pair of slopes but it is in fact a gradual rolloff. However, the non-linearity is quite small in the range 1 to 100 rad. Ways of handling this non-linearity are an important part of future research in RADFET methodology.

In Fig. 5.1, the positive-bias curve is expressed as a straight line but, if the curve were taken to higher doses, it would also roll off. The tendency to under-read at higher doses is intrinsic in the RADFET principle whatever the bias applied. As charge builds up in the oxide, the response is smaller. Trapping events are fewer and the increasing built - in field makes electron-hole separation less likely. Despite the non-linearity, as demonstrated in Fig. 5.1, the growth curve for zero bias exposure is smooth and there is a unique value of delta V(T) for a given dose, which can be "looked up". In fact, the slope of the line changes smoothly (Holmes-Siedle et al 1986; August et al 1984). The non-linearity is quite small in the 1 to 100 rad range. The zero bias mode exhibits compensating fundamental advantages, particularly that stress on the oxides and the resultant drift, are minimized. Dosimeter "lockets" and accident badges can then also operate without a battery. Of course, the minimum resolvable dose is lower but it is thought that doses of the order of 1 rad can be resolved.

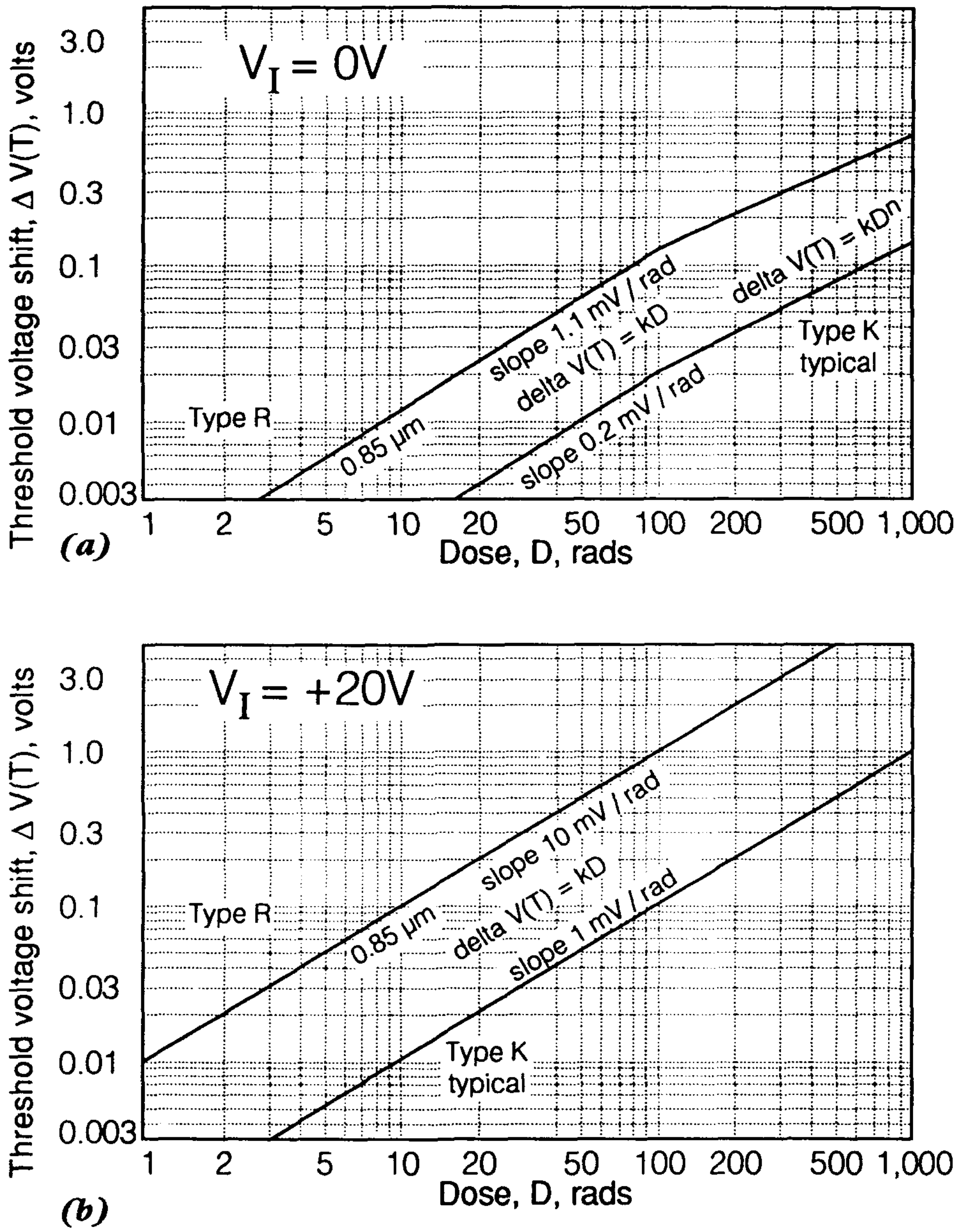


Fig. 5.1 Nominal response curves for the TOT500 RADFET, in two modes
(a) Zero bias during irradiation ($V_I = 0$)
(b) Positive bias during irradiation ($V_I = +20V$)

5.2.2. Pulsed Radiation

Because of the use of tactical dosimeters in pulsed radiation environments, the question of dependence of RADFET response on the rate of delivery of the dose has been the subject of much study and testing by CECOM (Bechtel et al 1991; Osman, 1991). Work by Kronenberg and colleagues in the 1988-90 period raised the possibility that responses under zero bias in pulsed radiation beams yield enhanced responses, possibly due to the generation of an internal photovoltage which draws holes towards the silicon. These results are discussed in a REM scientific report to CECOM (Holmes-Siedle 1991). More recently, CECOM have issued a scientific report "Parameters for consideration in the selection of a PMOSFET detector suitable for tactical personnel dosimetry" (Bechtel et al 1991), in which some more recent results are included.

The question of whether high dose rates seriously affect dosimeter sensitivity in the 100 rad range has only been investigated by the Fort Monmouth group. However, there is much previous evidence to suggest that MOS devices irradiated under bias should not be so affected. MOS transistors of many kinds have been pulsed in Flash X-rays (Holmes-Siedle and Adams, 1992). and no damage over and above the expected interface and ionization charge has been observed. However, most of those devices were not operated as detectors.

5.2.3 Oxide thickness vs. Responsivity - Model

Figure 5.2 shows the guidelines which REM is using to define responsivity versus oxide thickness. The straight lines shown represent equations for zero bias and positive bias irradiation of oxides at constant field, based on work by SUMC and REM, funded by ESTEC (Ensell et al 1988). The RADFET pattern used in this work was the TOT300 mask, not the TOT500 layout used in the CECOM contractS. The oxide processing has also altered since 1988. The TOT501 series yielded responsivity values better than those predicted by the curves (see previous REM reports).

The model in Fig 5.2 assumes that the responsivity of a RADFET increases as the square of the oxide thickness. Therefore, the target thickness of 1.25 micrometres is capable of increasing responsivity by a factor greater than 2. However, it should be noted that the zero-bias performance of the thermal/CVD sandwich oxide, represented in Fig 5.2 by the data points at d(ox)= 2.3µm, fell BELOW the trend line, suggesting that we should not expect a twofold gain by going from 0.85 to 1.25 micrometres, but something less. The actual goals for responsivity (proprietary) given to CECOM in the contract plan, were centred on an improvement of 50 percent in zero-bias responsivity.

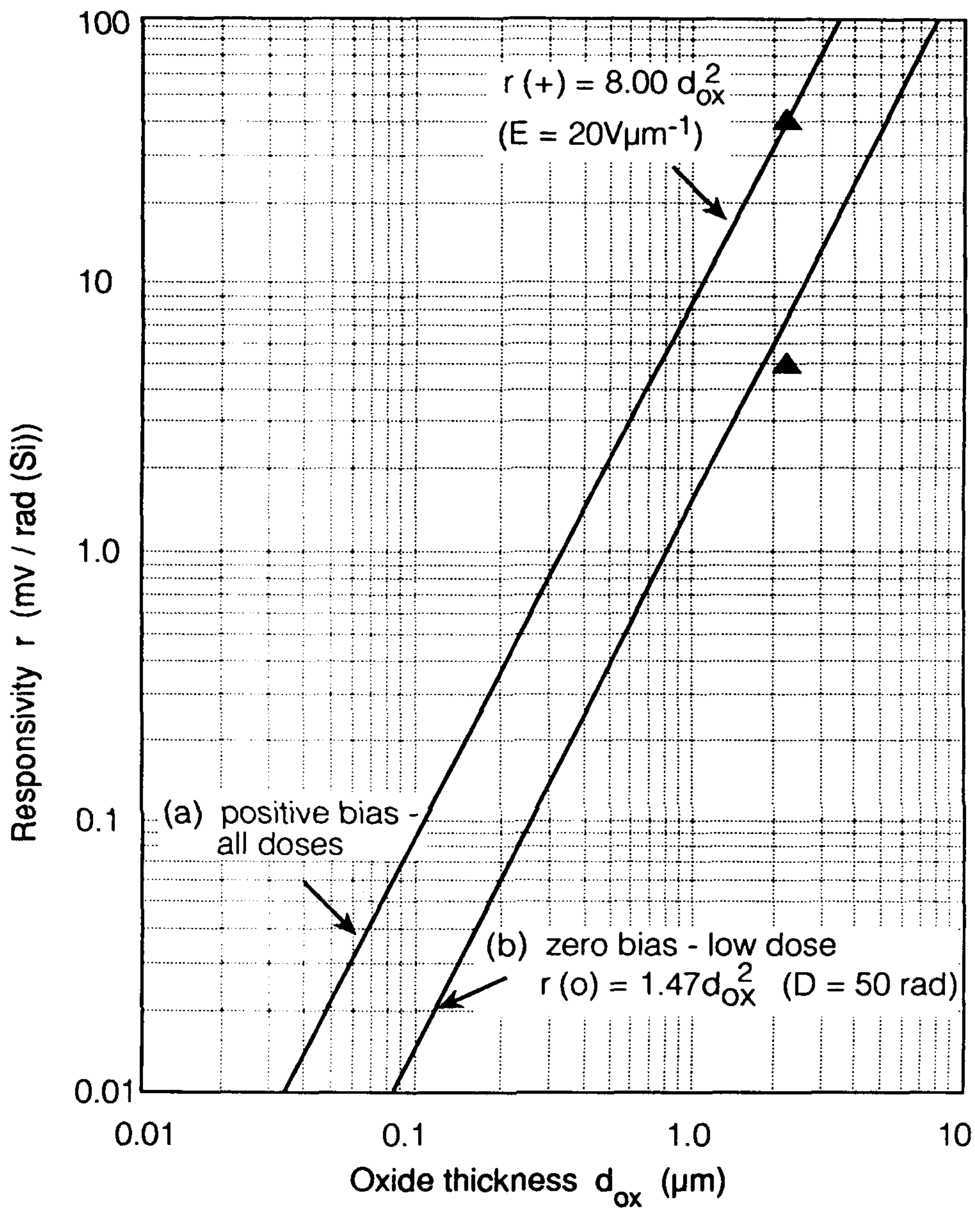


Fig. 5.2 Summary of trends in RADFET Responsivity vs. Oxide Thickness at Low Doses (50 rad) - Model: (a) positive bias, 20 V/μm field (b) zero bias Data point at 2.3μm shows the thickest (sandwich) oxide made in an earlier research project (Ensell et al 1988).

5.3 Experimental Details

5.3.1 Radiation Test Sources

Radiation tests on prototypes were performed at three facilities:

Co-60 Teletherapy source, Churchill Hospital, Oxford, UK

The EROS 4 Megavolt Flash X-ray source, Aldermaston, UK

Copper target X - ray machine, BNF Fulmer, Wantage, UK

Cobalt-60 radiation, because it is highly penetrating, is not strongly interfered with by device packaging. This radiation is often used as a standard source for evaluating responsivity. The source at the Churchill Hospital is mapped accurately in terms of rads(tissue).

To investigate the relative responses under Co-60 and pulsed radiation, it was decided to use the EROS Flash X-Ray machine in the UK. This was arranged by REM and an official request was then sent by the European Research Office of the US Army (Dr. R. Seiders), to the Superintendent of Radiation Effects, Dr. Max Gunnerson at AWE, Aldermaston, a branch of the UK Ministry of Defence. The machine is used for the testing of devices under pulsed X-rays up to the maximum intensities expected for military equipment in the field (over 1E10 rad/sec). A 4 MeV pulsed electron beam strikes a tantalum target and samples can be placed in the beam room at measured distances varying from centimetres to metres from the target. Beam doses given to the RADFETs were measured shot for shot by thermoluminescent dosimetry (TLD), silicon p-i-n diode responses and silicon calorimetry (AWE Dosimetry Service).

Intensive preparations were made by REM and the experiments were performed June 3,4,5 and 6. This included the first - time use of the Co-60 therapy source at the Churchill hospital, Oxford and the first-time use of a microcomputer for logging data from the RADFET reader. Software was written in Basic. The logged results are tabulated with the calculated responsivity and stability values.

5.3.2 Irradiation with Steady-State X-Rays

A. General

The X - ray measurements were performed first, to obtain relative performance of the 0.85. 0.95, 1.03 and 1.24 micrometre oxides. Absolute doses were difficult to calculate due to the interference of packaging variability with this strongly scattered type of radiation. Growth curves for all samples was smooth and repeatable with times of X-ray exposure. Dosimetry depended on the extensive previous calibration of the 0.85 um oxides, using Co-60 sources calibrated with ion chambers and TLDs. The intermediate thickness as not studied because the production of packaged prototypes of wafer 17 chips failed.

The following types were compared under X-Rays:

TOT501C-2-3	Wafer 2	0.85um	DIL, delidded *
TOT501C-8-3	8	0.85	CC-3 **
TOT502A-14-1	14	0.95	CC-3
TOT504A-19-1	19	1.24	CC-3

* ceramic header with standard gold ink ; device in air

** polymeric chip carrier with minimum gold; encapsulated with silica-filled epoxy (glob top)

B. Method

The devices in DIL packages were delidded and a thin paper cover applied to protect against mishandling. In one case, a drop of polystyrene cement was placed over the chip, to assess the effect of air vs. organic as the encapsulant. The CC-3 devices had the conventional glob top encapsulation which, since there was less than 0.5 mm thickness over the top of the chip was thought would not attenuate the X-rays significantly.

To suppress the Copper K-lines (about 8 keV) , four iron filters of 25 um each were placed over the tube window. Spectra taken with a graphite monochromator showed that no K-lines emerged whatsoever. The emerging X-rays lay in energy between the Fe K-edge (about 15 keV) and the maximum tube potential, 40 keV. The plots showed that the spectrum was flat in that region. The devices were exposed one at a time in the beam. The sequence followed was one frequently used ny REM to characterize RADFETS. The following sequence of bias and dose values gives both zero bias curve shape and bias dependence data:

GATE BIAS	TOTAL DOSES *
zero	5, 10, 12, 15, 20, 30, 40, 50, 70, 90, 100, 150, 200
+5V	5, 10
+10	5, 10
+20	5, 10

* nominal dose values based on an assumed dose rate of 1 rad/sec

The need for many shots at zero bias is to obtain the shape of the non-linear response. Under bias, subsebquent shots are undesirable because they have the same value as the first two

except for very slight incipient saturation effects. The biassed shots which go before do not greatly affect the responsivity values obtained for later ones.

C. Data

The results of this experiment are summarized in Table 5.1. The responses in mV obtained from the 5 rad point are compared.

TABLE 5.1 Threshold shifts in mV for exposure to a nominal 5 rad (5-second) shot of copper tube X-rays filtered through 100 um iron using 40 kV potential and 5 mA tube current

Wafer No.	2	8	14	19
t(ox)	0.85	0.85	0.95	1.26 micrometres
Bias				
0	6	5.5	4.5	8.0
+5	24	24	34	45
+10	42	42	58	72
+20	60	60	88	105

This shows that the 1.26 μm oxide is over 30 percent better at zero bias and 80 percent better at +20V bias.

5.3.3 Co-Ordinated Cobalt and Flash X-Ray Tests

A. Methods

The object of the test was to show up differences between RADFET response at low dose rate (Co-60 at about 1 rad/sec) and Flash X-ray at about 1E9 rad/sec. This was similar to the tests carried out by CECOM in 1989-90 at Aberdeen and Fort Monmouth. In each case there was a gamma exposure, then a "Field Test", usually the high-rate source, then another gamma exposure on the same sample. Unlike the US tests, only the zero bias condition was examined, in order to conserve time and increase sample numbers.

Some samples had a larger number of shots of Cobalt-60 only, so as to establish the growth curve for low-dose rate radiation over

the whole range of doses to be examined (1 to 500 rad). For tactical purposes, the region from zero to 100 rads is probably of particular interest. Accordingly, the pre-calibrating Cobalt shots were 10, 40 and 50 rads and the post field test shots 50 and 50 rads. The Flash X-ray shots were left flexible, since machine output varies with the day but plans were based on 100 rads per shot.

Several months after these tests, similar tests were done by CECOM using REM's Delivery 1AA, including similar devices. Growth curves for steady-state gammas were made with Cs-137 at Fort Monmouth and shots of 4 MeV flash X-rays were made at Aberdeen, MD over slightly larger dose ranges. These tests have supplied data which enhances confidence in our own results and they are cited in various places on graphs and in the text in this spirit.

Dosimetry for gamma rays was supplied by the Churchill hospital, using mapped positions in the Teletherapy radiation field (rad(tissue)). Dosimetry for the FX was supplied by the Dosimetry Service of the Atomic Weapons Establishment of the UK MInistry of Defence (Head, Dr. R. Harris), using two kinds of TLD and other specialized characterization methods.

The first series of pulsed X-ray shots was aimed at establishing whether or not shorting in foam gave a response similar to that obtained with metallic shorts. One RADFET was put in a hard-wired socket with all leads shorted with soldered connections. Other devices were placed in foam. Three Flash X-ray bursts were administered. On a quick look, the Threshold voltage shiftf on all of the devices were quite well matched and so, to allow more devices per shot to be packed into the beam area , conductive foam was used for the two subsequent series of exposures. The same sequence applied to the gamma ray shots.

Table 5.2 gives a list of the devices which were exposed to gamma rays and/or flash X-rays during the tests made between June 3 and 6th, 1991.

Table 5.2 Test Samples ; Construction and Radiation Test Notes

TOT501C-2-3 (DIL with Kovar lid - standard gold content)
16 Co (9 May)
17 Co/FX
27 FX 5 June
28 "
29 "

TOT501C-2-4 (DIL with ceramic lid - low gold content)
1 Co/FX/Co 3-6 June
2 "
3 "
4 FX/Co 4-6 June (FX 98,99,500)
5 "
6 "
7 "
8 "
9 FX only (503,504,505)
10 "
11 "
12 FX only (505 survival)

TOT501C-2-6 (Chip Carrier std epoxy glob)
2 Co precal curve (91-99)
3 Co (31,32,33)

TOT501C-8-2 (Chip Carrier std epoxy glob)
5 FX only (survival)

TOT501C-8-3 (Chip Carrier std epoxy glob)
2 reserve
3 Co/FX/Co
4 Co/FX/Co

TOT502A-14-1 (Chip Carrier std epoxy glob)
3 Co/FX/Co
4 "
5 reserve
6 Co/Co (31,32,61,63)
7 FX(cal)
8 "
9 "

TOT502A-19-1 (Chip Carrier std epoxy glob)
8 FX(cal)
2 FX(survival)
5 Co/FX/Co
6 Co (91,92,93)
7 Co/FX/Co
9 "
10 "
13 "
15 FX(cal)
16 "
17 "

5.3.3 cont.

B. Results

Tables 5.3 to 5.10 show examples of the analysis of device responses using a spreadsheet (1-2-3 type). In the main test, (named "Co/FX/Co" in Table 5.2), three cobalt "precal" shots are followed by three Flash X-ray shots and then two Cobalt shots.

Figure 5.3(a) shows a plot of the responses of 0.85 micrometre thick pMOS FETs No. 501C-2-4 # 3 and 4. These were irradiated with gammas, then pulsed X-rays then gammas ("Co/FX/Co" test in the tables) at zero applied bias. On the same plot, we have superimposed the growth curves later obtained by CECOM for gamma rays and flash X-rays. The CECOM X-ray exposures shown here were done without any pre-cal gamma rays. A comparison of the two sets will be discussed later.

Figure 5.3(b) shows a plot of samples 504A-19-1 # 9. 10 and 13. These 1.26 micrometre oxides were were irradiated at the same time in the same conditions. It is clear that the growth curve lies about 50 percent above that for the "old" chips at all points, possibly converging slightly at higher doses.

The above are a sampling of the data. A study of the rest of the raw data by the author and Dr. Cohen shows similar trends in responses to pulsed X-rays and gamma rays. It is proposed that the rest of the data be analyzed if required, in future collaborations with CECOM.

C. Discussion of results

The plots of low-rate cobalt and the pulsed X-ray shots appear to be roughly "in line" i.e. give a smooth growth curve, similar to that found for RADFETs exposed, under zero bias, to a similar series of doses of gamma rays only. This suggests that the scale of dose rate effects supplies only a secondary perturbation to zero-bias response. However, closer inspection of the responsivity step by step, described below, and cross-comparison with the CECOM curves shows different features in low and high dose rate exposures, some possibly due to experimental technique but others possibly basic in nature.

The CECOM curves for zero applied bias exhibited two important characteristics. Firstly the Flash X-ray curves showed responses which were enhanced with respect to the gamma curves. This could be real or could be a dosimetry mismatch between the Cs-137 at 0.5 MeV and the FX at 1 to 4 MeV). Secondly, the Flash X-ray responses, although only based on a few dose values, appear to be LINEAR with dose, unlike the gamma curves. This cannot be explained by dosimetry mismatches and strongly suggests that the "zero bias" condition does not represent zero field across the oxide. Kronenberg indeed suggested that pulsed photocurrents could place a positive voltage on the gate despite the attempted shorting of the electrodes. On examination of the plots for the REM Test in Figs 5.3(a) and (b) one can see indications of a

Table 5.3

RADIATION TEST RECORD ;file rad-024.wks ; Co/FX/Co ; June 3-6, 1991
RADFET Sample No. TOT501C-2-4 #1
V(I) = 0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	6.038	0	0		
Co	31	10.1	10.1	6.051	13	13	1.29	1.29
Co	32	40.1	50.2	6.093	42	55	1.10	1.05
Co	33	50.5	100.7	6.137	44	99	0.98	0.87
FX	501	80.6	181.3	6.244	107	206	1.14	1.33
FX	502	81.7	263.0	6.346	102	308	1.17	1.25
FX	505	98.0	361.0	6.410	64	372	1.03	0.65
Co	61	50.5	411.5	6.434	24	396	0.96	0.48
Co	62	50.5	462.0	6.460	26	422	0.91	0.51
RADFET Q1								
		0.0	0.0	6.063	0	0		
Co	31	10.1	10.1	6.077	14	14	1.39	1.39
Co	32	40.1	50.2	6.118	41	55	1.10	1.02
Co	33	50.5	100.7	6.163	45	100	0.99	0.89
FX	501	80.6	181.3	6.281	118	218	1.20	1.46
FX	502	81.7	263.0	6.381	100	318	1.21	1.22
FX	505	98.0	361.0	6.462	81	399	1.11	0.83
Co	61	50.5	411.5	6.488	26	425	1.03	0.51
Co	62	50.5	462.0	6.511	23	448	0.97	0.46
RADFET Q2								
		0.0	0.0	2.786	0	0		
Co	31	10.1	10.1	2.787	1	1	0.10	0.10
Co	32	40.1	50.2	2.793	6	7	0.14	0.15
Co	33	50.5	100.7	2.799	6	13	0.13	0.12
FX	501	80.6	181.3	2.813	14	27	0.15	0.17
FX	502	81.7	263.0	2.827	14	41	0.16	0.17
FX	505	98.0	361.0	2.838	11	52	0.14	0.11
Co	61	50.5	411.5	2.846	8	60	0.15	0.16
Co	62	50.5	462.0	2.852	6	66	0.14	0.12
RADFET Q3								
		0.0	0.0	2.859	0	0		
Co	31	10.1	10.1	2.861	2	2	0.20	0.20
Co	32	40.1	50.2	2.867	6	8	0.16	0.15
Co	33	50.5	100.7	2.873	6	14	0.14	0.12
FX	501	80.6	181.3	2.887	14	28	0.15	0.17
FX	502	81.7	263.0	2.901	14	42	0.16	0.17
FX	505	98.0	361.0	2.910	9	51	0.14	0.09
Co	61	50.5	411.5	2.918	8	59	0.14	0.16
Co	62	50.5	462.0	2.924	6	65	0.14	0.12

Table 5.4

RADIATION TEST RECORD ;file rad-025.wks ;Co-60/FX/Co-60 ; June 3-6 1991
RADFET Sample No. TOT501C-2-4 #3
V(I) = 0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	5.859	0	0		
Co	31	10.1	10.1	5.872	13	13	1.29	1.29
Co	32	40.1	50.2	5.917	45	58	1.16	1.12
Co	33	50.5	100.7	5.968	51	109	1.08	1.01
FX	501	80.6	181.3	6.087	119	228	1.26	1.48
FX	502	81.7	263.0	6.203	116	344	1.31	1.42
FX	505	98.0	361.0	6.275	72	416	1.15	0.73
Co	61	50.5	411.5	6.295	20	436	1.06	0.40
Co	62	50.5	462.0	6.321	26	462	1.00	0.51
RADFET Q1								
		0.0	0.0	5.895	0	0		
Co	31	10.1	10.1	5.908	13	13	1.29	1.29
Co	32	40.1	50.2	5.952	44	57	1.14	1.10
Co	33	50.5	100.7	5.998	46	103	1.02	0.91
FX	501	80.6	181.3	6.108	110	213	1.17	1.36
FX	502	81.7	263.0	6.194	86	299	1.14	1.05
FX	505	98.0	361.0	6.276	82	381	1.06	0.84
Co	61	50.5	411.5	6.298	22	403	0.98	0.44
Co	62	50.5	462.0	6.325	27	430	0.93	0.53
RADFET Q2								
		0.0	0.0	2.719	0	0		
Co	31	10.1	10.1	2.721	2	2	0.20	0.20
Co	32	40.1	50.2	2.726	5	7	0.14	0.12
Co	33	50.5	100.7	2.733	7	14	0.14	0.14
FX	501	80.6	181.3	2.746	13	27	0.15	0.16
FX	502	81.7	263.0	2.759	13	40	0.15	0.16
FX	505	98.0	361.0	2.768	9	49	0.14	0.09
Co	61	50.5	411.5	2.774	6	55	0.13	0.12
Co	62	50.5	462.0	2.781	7	62	0.13	0.14
RADFET Q3								
		0.0	0.0	2.688	0	0		
Co	31	10.1	10.1	2.690	2	2	0.20	0.20
Co	32	40.1	50.2	2.695	5	7	0.14	0.12
Co	33	50.5	100.7	2.710	15	22	0.22	0.30
FX	501	80.6	181.3	2.716	6	28	0.15	0.07
FX	502	81.7	263.0	2.731	15	43	0.16	0.18
FX	505	98.0	361.0	2.742	11	54	0.15	0.11
Co	61	50.5	411.5	2.748	6	60	0.15	0.12
Co	62	50.5	462.0	2.755	7	67	0.15	0.14

Table 5.5

RADIATION TEST RECORD ; file rad-191.wks : Co/FX/Co : June 3-6, 1991
DEVICE NO. 504A-19-1#9
V(I)=0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	VTQ4 (V)	SHIFT (SHOT) (mV)	SHIFT (TOT) (mV)	OVERALL RESPONSIV (mV/rad)	STEP RESPONSIV (mV/rad)
RADFET Q4								
		0.0	0.0	10.001	0	0		
Co	31	10.1	10.1	10.051	50	50	4.95	4.95
Co	32	40.1	50.2	10.134	83	133	2.65	2.07
Co	33	50.5	100.7	10.218	84	217	2.15	1.66
FX	501	80.6	181.3	10.312	94	311	1.72	1.17
FX	502	81.7	263.0	10.394	82	393	1.49	1.00
FX	505	98.0	361.0	10.494	100	493	1.37	1.02
Co	61	50.5	411.5	10.529	35	528	1.28	0.69
Co	62	50.5	462.0	10.560	31	559	1.21	0.61
RADFET Q1								
		0.0	0.0	10.076	0	0		
Co	31	10.1	10.1	10.095	19	19	1.92	1.92
Co	32	40.1	50.2	10.170	75	94	1.87	1.86
Co	33	50.5	100.7	10.245	75	169	1.68	1.49
FX	501	80.6	181.3	10.350	105	274	1.51	1.30
FX	502	81.7	263.0	10.464	114	388	1.47	1.40
FX	505	98.0	361.0	10.533	69	457	1.27	0.70
Co	61	50.5	411.5	10.569	36	493	1.20	0.71
Co	62	50.5	462.0	10.603	34	527	1.14	0.67
RADFET Q2								
		0.0	0.0	3.108	0	0		
Co	31	10.1	10.1	3.109	1	1	0.10	0.10
Co	32	40.1	50.2	3.111	2	3	0.06	0.05
Co	33	50.5	100.7	3.114	3	6	0.06	0.06
FX	501	80.6	181.3	3.117	3	9	0.05	0.04
FX	502	81.7	263.0	3.122	5	14	0.05	0.06
FX	505	98.0	361.0	3.125	3	17	0.05	0.03
Co	61	50.5	411.5	3.128	3	20	0.05	0.06
Co	62	50.5	462.0	3.130	2	22	0.05	0.04
RADFET Q3								
		0.0	0.0	3.094	0	0		
Co	31	10.1	10.1	3.095	1	1	0.10	0.10
Co	32	40.1	50.2	3.097	2	3	0.06	0.05
Co	33	50.5	100.7	3.100	3	6	0.06	0.06
FX	501	80.6	181.3	3.103	3	9	0.05	0.04
FX	502	81.7	263.0	3.108	5	14	0.05	0.06
FX	505	98.0	361.0	3.111	3	17	0.05	0.03
Co	61	50.5	411.5	3.114	3	20	0.05	0.06
Co	62	50.5	462.0	3.116	2	22	0.05	0.04

Table 5.6

RADIATION TEST RECORD ; file rad-192.wks ;Co/FX/Co ; June 3-6 1991
DEVICE NO. 504A-19-1 #10
V(I)=0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	9.992	0	0		
Co	31	10.1	10.1	10.021	29	29	2.87	2.87
Co	32	40.1	50.2	10.097	76	105	2.09	1.90
Co	33	50.5	100.7	10.173	76	181	1.80	1.50
FX	501	80.6	181.3	10.260	87	268	1.48	1.08
FX	502	81.7	263.0	10.332	72	340	1.29	0.88
FX	505	98.0	361.0	10.419	87	427	1.18	0.89
Co	61	50.5	411.5	10.459	40	467	1.13	0.79
Co	62	50.5	462.0	10.491	32	499	1.08	0.63
RADFET Q1								
		0.0	0.0	9.941	0	0		
Co	31	10.1	10.1	9.965	24	24	2.38	2.38
Co	32	40.1	50.2	10.037	72	96	1.91	1.80
Co	33	50.5	100.7	10.064	27	123	1.22	0.53
FX	501	80.6	181.3	10.235	171	294	1.62	2.12
FX	502	81.7	263.0	10.360	125	419	1.59	1.53
FX	505	98.0	361.0	10.431	71	490	1.36	0.72
Co	61	50.5	411.5	10.463	32	522	1.27	0.63
Co	62	50.5	462.0	10.494	31	553	1.20	0.61
RADFET Q2								
		0.0	0.0	3.059	0	0		
Co	31	10.1	10.1	3.060	1	1	0.10	0.10
Co	32	40.1	50.2	3.062	2	3	0.06	0.05
Co	33	50.5	100.7	3.065	3	6	0.06	0.06
FX	501	80.6	181.3	3.069	4	10	0.06	0.05
FX	502	81.7	263.0	3.074	5	15	0.06	0.06
FX	505	98.0	361.0	3.078	4	19	0.05	0.04
Co	61	50.5	411.5	3.079	1	20	0.05	0.02
Co	62	50.5	462.0	3.082	3	23	0.05	0.06
RADFET Q3								
		0.0	0.0	3.060	0	0		
Co	31	10.1	10.1	3.061	1	1	0.10	0.10
Co	32	40.1	50.2	3.063	2	3	0.06	0.05
Co	33	50.5	100.7	3.066	3	6	0.06	0.06
FX	501	80.6	181.3	3.070	4	10	0.06	0.05
FX	502	81.7	263.0	3.074	4	14	0.05	0.05
FX	505	98.0	361.0	3.077	3	17	0.05	0.03
Co	61	50.5	411.5	3.079	2	19	0.05	0.04
Co	62	50.5	462.0	3.082	3	22	0.05	0.06

Table 5.7

RADIATION TEST RECORD ;file rad-193.wks
Co60/FX/Co60; June 3-6, 1991
RADFET Sample No. TOT504A-19-1 #13
V(I) = 0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	9.588	0	0		
Co	31	10.1	10.1	9.618	30	30	2.97	2.97
Co	32	40.1	50.2	9.694	76	106	2.11	1.90
Co	33	50.5	100.7	9.771	77	183	1.82	1.52
FX	501	80.6	181.3	9.847	76	259	1.43	0.94
FX	502	81.7	263.0	9.912	65	324	1.23	0.80
FX	505	98.0	361.0	10.007	95	419	1.16	0.97
Co	61	50.5	411.5	10.039	32	451	1.10	0.63
Co	62	50.5	462.0	10.086	47	498	1.08	0.93
RADFET Q1								
		0.0	0.0	9.588	0	0		
Co	31	10.1	10.1	9.616	28	28	2.77	2.77
Co	32	40.1	50.2	9.689	73	101	2.01	1.82
Co	33	50.5	100.7	9.761	72	173	1.72	1.43
FX	501	80.6	181.3	9.900	139	312	1.72	1.72
FX	502	81.7	263.0	10.034	134	446	1.70	1.64
FX	505	98.0	361.0	10.121	87	533	1.48	0.89
Co	61	50.5	411.5	10.144	23	556	1.35	0.46
Co	62	50.5	462.0	10.180	36	592	1.28	0.71
RADFET Q2								
		0.0	0.0	3.060	0	0		
Co	31	10.1	10.1	3.061	1	1	0.10	0.10
Co	32	40.1	50.2	3.063	2	3	0.06	0.05
Co	33	50.5	100.7	3.065	2	5	0.05	0.04
FX	501	80.6	181.3	3.069	4	9	0.05	0.05
FX	502	81.7	263.0	3.075	6	15	0.06	0.07
FX	505	98.0	361.0	3.078	3	18	0.05	0.03
Co	61	50.5	411.5	3.081	3	21	0.05	0.06
Co	62	50.5	462.0	3.083	2	23	0.05	0.04
RADFET Q3								
		0.0	0.0	3.080	0	0		
Co	31	10.1	10.1	3.082	2	2	0.20	0.20
Co	32	40.1	50.2	3.083	1	3	0.06	0.02
Co	33	50.5	100.7	3.085	2	5	0.05	0.04
FX	501	80.6	181.3	3.085	0	5	0.03	0.00
FX	502	81.7	263.0	3.089	4	9	0.03	0.05
FX	505	98.0	361.0	3.092	3	12	0.03	0.03
Co	61	50.5	411.5	3.094	2	14	0.03	0.04
Co	62	50.5	462.0	3.097	3	17	0.04	0.06

Table 5.8

RADIATION TEST RECORD ;file rad-021.wks ; Co-60 ; May 9, 1991
RADFET Sample No. TOT501C-2-3 #34 ; V(I) = 0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	5.696	0	0		
Co	1	5.2	5.2	5.703	7	7	1.35	1.35
Co	2	5.2	10.4	5.712	9	16	1.54	1.73
Co	3	5.2	15.6	5.720	8	24	1.54	1.54
Co	4	10.2	25.8	5.728	8	32	1.24	0.78
Co	5	10.2	36.0	5.744	16	48	1.33	1.57
Co	5	10.2	46.2	5.758	14	62	1.34	1.37
Co	6	20.2	56.2	5.790	32	94	1.67	1.58
Co	7	20.2	76.4	5.815	25	119	1.56	1.24
RADFET Q1								
		0.0	0.0	5.709	0	0		
Co	1	5.2	5.2	5.718	9	9	1.73	1.73
Co	2	5.2	10.4	5.727	9	18	1.73	1.73
Co	3	5.2	15.6	5.736	9	27	1.73	1.73
Co	4	10.2	25.8	5.744	8	35	1.36	0.78
Co	5	10.2	36.0	5.761	17	52	1.44	1.67
Co	6	10.2	46.2	5.777	16	68	1.47	1.57
Co	7	20.2	56.2	5.809	32	100	1.78	1.58
Co	8	20.2	76.4	5.835	26	126	1.65	1.29
Co	9	5.2	81.6	5.864	29	155	1.90	5.58
RADFET Q2								
		0.0	0.0	2.449	0	0		
Co	1	5.2	5.2	2.489	40	40	7.69	7.69
Co	2	5.2	10.4	2.450	-39	1	0.10	-7.50
Co	3	5.2	15.6	2.427	-23	-22	-1.41	-4.42
Co	4	10.2	25.8	2.510	83	61	2.36	8.14
Co	5	10.2	36.0	2.512	2	63	1.75	0.20
Co	6	10.2	46.2	2.515	3	66	1.43	0.29
Co	7	20.2	56.2	2.520	5	71	1.26	0.25
Co	8	20.2	76.4	2.527	7	78	1.02	0.35
Co	9	5.2	81.6	2.523	-4	74	0.91	-0.77
RADFET Q3								
		0.0	0.0	2.511	0	0		
Co	1	5.2	5.2	2.508	-3	-3	-0.58	-0.58
Co	2	5.2	10.4	2.517	9	6	0.58	1.73
Co	3	5.2	15.6	2.582	65	71	4.55	12.50
Co	4	10.2	25.8	2.513	-69	2	0.08	-6.76
Co	5	10.2	36.0	2.520	7	9	0.25	0.69
Co	6	10.2	46.2	2.524	4	13	0.28	0.39
Co	7	20.2	56.2	2.528	4	17	0.30	0.20
Co	8	20.2	76.4	2.529	1	18	0.24	0.05
Co	9	5.2	81.6	2.534	5	23	0.28	0.96

Table 5.9

RADIATION TEST RECORD ;file rad-141.wks ; Co-60 ; May 9, 1991
RADFET Sample No. TOT504A-14-1 #3 ; V(I) = 0

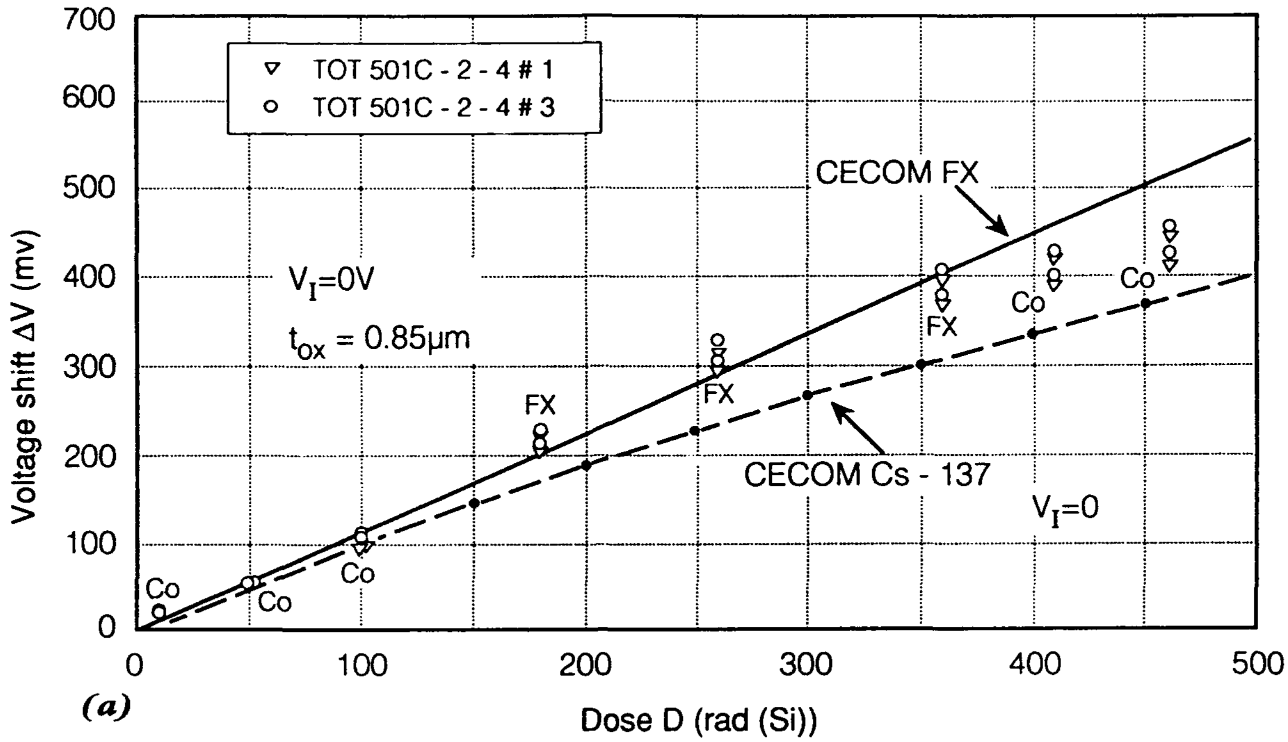
RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4 and Q1 (identical data)								
		0.0	0.0	7.628	0	0		
Co	1	5.2	5.2	7.637	9	9	1.73	1.73
Co	2	5.2	10.4	7.644	7	16	1.54	1.35
Co	3	5.2	15.6	7.651	7	23	1.47	1.35
Co	4	5.2	20.8	7.658	7	30	1.44	1.35
Co	4a	10.2	31.0	7.671	13	43	1.39	1.27
Co	5	10.2	41.2	7.684	26	56	1.36	2.55
Co	6	10.2	51.4	7.696	12	68	1.32	1.18
Co	7	20.0	71.4	7.719	23	91	1.27	1.15
Co	8	20.0	91.4	7.741	22	113	1.24	1.10
Co	9	20.0	111.4	7.761	20	133	1.19	1.00
Co	10	50.0	161.4	7.806	45	178	1.10	0.90
Co	11	50.0	211.4	7.846	40	218	1.03	0.80
Co	12	200.0	411.4	7.985	139	357	0.87	0.70
Co	13	200.0	611.4	8.101	116	473	0.77	0.58
RADFET Q2								
		0.0	0.0	2.461	0	0		
Co	1	5.2	5.2	2.461	0	0	0.000	0.00
Co	2	5.2	10.4	2.461	0	0	0.000	0.00
Co	3	5.2	15.6	2.461	0	0	0.000	0.00
Co	4	5.2	20.8	2.462	1	1	0.048	0.19
Co	4a	10.2	31.0	2.462	0	1	0.032	0.00
Co	5	10.2	41.2	2.463	1	2	0.049	0.10
Co	6	10.2	51.4	2.464	1	3	0.058	0.10
Co	7	20.0	71.4	2.465	1	4	0.056	0.05
Co	8	20.0	91.4	2.465	0	4	0.044	0.00
Co	9	20.0	111.4	2.467	2	6	0.054	0.10
Co	10	50.0	161.4	2.469	2	8	0.050	0.04
Co	11	50.0	211.4	2.471	2	10	0.047	0.04
Co	12	200.0	411.4	2.481	10	20	0.049	0.05
Co	13	200.0	611.4	2.491	10	30	0.049	0.05
RADFET Q3								
		0.0	0.0	2.455	0	0		
Co	1	5.2	5.2	2.455	0	0	0.000	0.00
Co	2	5.2	10.4	2.456	1	1	0.096	0.19
Co	3	5.2	15.6	2.456	0	1	0.064	0.00
Co	4	5.2	20.8	2.456	0	1	0.048	0.00
Co	4a	10.2	31.0	2.456	0	1	0.032	0.00
Co	5	10.2	41.2	2.456	0	1	0.024	0.00
Co	6	10.2	51.4	2.457	1	2	0.039	0.10
Co	7	20.0	71.4	2.457	0	2	0.028	0.00
Co	8	20.0	91.4	2.458	1	3	0.033	0.05
Co	9	20.0	111.4	2.459	1	4	0.036	0.05
Co	10	50.0	161.4	2.460	1	5	0.031	0.02
Co	11	50.0	211.4	2.462	2	7	0.033	0.04
Co	12	200.0	411.4	2.472	10	17	0.041	0.05
Co	13	200.0	611.4	2.483	11	28	0.046	0.05

Table 5.10

RADIATION TEST RECORD ; file rad-196.wks ; Co-60 ; May 9 1991
RADFET Sample No. TOT504A-19-1 #3
V(I) = 0

RAD. TYPE	SHOT NO.	SHOT DOSE (rad)	TOTAL DOSE (rad)	V(T) (40uA) (V)	SHIFT (SHOT) (mV)	SHIFT (TOTAL) (mV)	OVERALL RESPONS. (mV/rad)	STEP RESPONSIVITY (mV/rad)
RADFET Q4								
		0.0	0.0	9.291	0	0		
Co	1	5.2	5.2	9.300	9	9	1.73	1.73
Co	2	5.2	10.4	9.309	9	18	1.73	1.73
Co	3	5.2	15.6	9.316	7	25	1.60	1.35
Co	4	5.2	20.8	9.324	8	33	1.59	1.54
Co	5	10.2	31.0	9.340	16	49	1.58	1.57
Co	6	10.2	41.2	9.354	14	63	1.53	1.37
Co	7	20.0	61.2	9.383	29	92	1.50	1.45
Co	8	20.0	81.2	9.410	27	119	1.47	1.35
Co	9	20.0	101.2	9.431	21	140	1.38	1.05
Co	10	50.0	151.2	9.486	55	195	1.29	1.10
Co	11	50.0	201.2	9.536	50	245	1.22	1.00
Co	12	200.0	401.2	9.710	174	419	1.04	0.87
Co	13	200.0	601.2	9.861	151	570	0.95	0.75
RADFET Q1								
		0.0	0.0	9.221	0	0		
Co	1	5.2	5.2	9.230	9	9	1.73	1.73
Co	2	5.2	10.4	9.239	9	18	1.73	1.73
Co	3	5.2	15.6	9.248	9	27	1.73	1.73
Co	4	5.2	20.8	9.256	8	35	1.68	1.54
Co	5	10.2	31.0	9.272	16	51	1.65	1.57
Co	6	10.2	41.2	9.288	16	67	1.63	1.57
Co	7	20.0	61.2	9.319	31	98	1.60	1.55
Co	8	20.0	81.2	9.345	26	124	1.53	1.30
Co	9	20.0	101.2	9.370	25	149	1.47	1.25
Co	10	50.0	151.2	9.429	59	199	1.32	1.18
Co	11	50.0	201.2	9.480	51	241	1.20	1.02
Co	12	200.0	401.2	9.660	180	412	1.03	0.90
Co	13	200.0	601.2	9.813	153	557	0.93	0.76
RADFET Q2 and Q3 (identical data)						*		
		0.0	0.0	2.842	0	0		
Co	1	5.2	5.2	2.843	1	5	0.96	0.19
Co	2	5.2	10.4	2.843	0	5	0.48	0.00
Co	3	5.2	15.6	2.844	1	10	0.64	0.19
Co	4	5.2	20.8	2.844	0	10	0.48	0.00
Co	5	10.2	31.0	2.844	0	10	0.32	0.00
Co	6	10.2	41.2	2.845	1	15	0.36	0.10
Co	7	20.0	61.2	2.847	2	25	0.41	0.10
Co	8	20.0	81.2	2.847	0	25	0.31	0.00
Co	9	20.0	101.2	2.848	1	30	0.30	0.05
Co	10	50.0	151.2	2.851	3	45	0.30	0.06
Co	11	50.0	201.2	2.853	0	55	0.27	0.00
Co	12	200.0	401.2	2.863	10	105	0.26	0.05
Co	13	200.0	601.2	2.873	10	155	0.26	0.05

* shift x 5



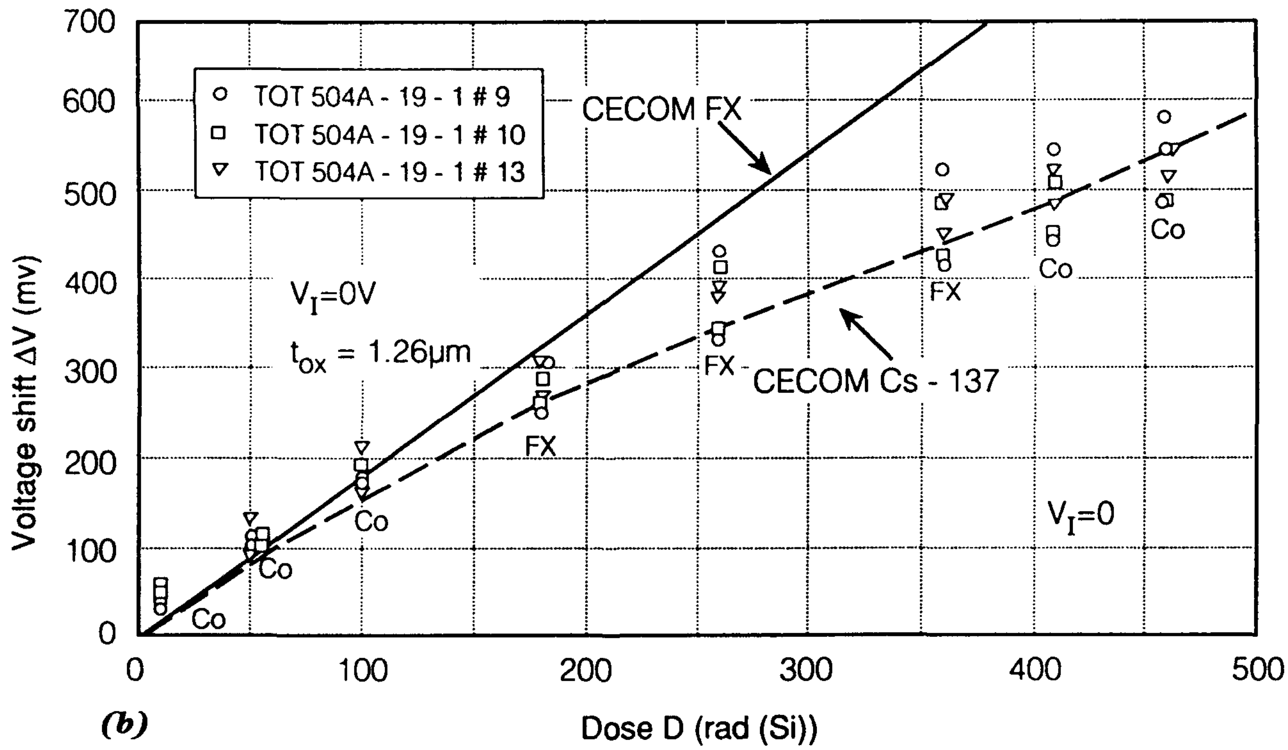


Fig. 5.3 Zero bias Growth Curves: Combined Co-60 and Flash X-ray experiment, June 1991
(a) 0.85µm (b) 1.26µm

tendency to follow the CECOM curves. That is, the three sets of points marked FX are on a higher slope than the three initial points marked Co. However, it should be noted that (a) the dosimetry on the third FX point is questionable and (b) after later tests by CECOM in 1992 (see e.g. Bechtel et al 1991), the FX points were found to lie closer to the gamma data thatn in the 1991 CECOM curves shown here (Kronenberg, private communication). Therefore, the degree of enhancement under pulsed radiation is still a matter requiring more exhaustive and conclusive tests.

The responsivity values in the "Overall responsivity" columns in the spreadsheet tables (5.3 to 5.10 and other data not included here) show that responsivity data for the same type is on the whole repeatable and smoothly changing with dose. It is, however also noted that the response for the 10 rad shot is usually about 30 percent larger than the next (50-rad) shot. This suggests that the low-dose response of the zero-bias mode may be very high and may bring 1-rad sensitivity within reach. This needs further research using shots of less than 1 rad, more precise temperature compensation and minimized oxide stress conditions.

The "Step Responsivity" column gives the average slope of the growth curve between two dose values. It is noticeable that, for Cobalt, the responses of a PAIR of thick-oxide FETS on the same chip is well matched. At the higher COBALT dose values it is usually within 10 percent. However, for the PULSED radiation, mismatch is sometimes over 50 percent. The reason for this is not yet clear although a model is given in the discussion. In the CECOM data the scatter in the result from device to device is typical plus/minus 5 percent for gamma rays and only slightly more for the few X-ray shots in the data given to REM, so the scatter does not seem to be intrinsic to pulsed exposure.

The expected "rolloff" in response with increasing dose (expected to be a power law, D. exp(0.66) , can be followed in the "step responsivity" column. The slope of the growth curve for the increment 400 to 460 rads is one third of the slope for the increment 10 to 50 rads. This rolloff is intrinsic to the zero-bias mode.

D. A model for scatter in pulsed exposures

It has been shown by Maier and Tallon (1974) that,in a pMOS FET exposed to pulsed radiation under zero bias, photocurrents generated by junctions can affect the amount of charge buildup. The effect of the current will be proportional to the transient voltages generated across the oxide; this in turn depends on the resistances in the silicon substrate and any resistances appearing between leads. With all leads inserted into a common conductor, these currents could affect the transient voltage appearing on the gate. The resistance of the foam between leads is probably thousands of ohms and could vary from lead to lead. Further experiments to characterize the effect are needed.

5.4 Fade

A question was raised by Dr. Kronenberg about "Room Temperature Annealing", that is changes in V(T) after irradiated devices are stored at room temperature (normally with leads in conductive foam). Most workers have seen increase in V(T) over about 3 days. This is consistent with the buildup of additional positive charge at the Si/SiO2 interface (see "rebound" effects in CMOS devices, for example in the book by Holmes-Siedle and Adams, OUP, 1992). In dosimeters, the effect could rightly be called "reverse fade".

REM checked samples irradiated in April - May 1 1992. Samples showed only minor postirradiation changes at room - temperature. Changes in v(T), whether encapsulated with air or epoxy, were less than 10 percent (usually growth of V(T)) over 30 days. That is within the expected limits.

5.5 Photocurrent Compensation

The work of Maier and Tallon (1974) showed that,in a pMOS FET exposed to pulsed radiation under zero bias, photocurrents generated by junctions can affect the amount of charge buildup. This is a special case of the normal "solar cell" action of RADFET junctions under any light. In Fig. 5.4, our curve-tracer readings for the TOT500 junctions show the result for all of the junctions of one chip (sources and drains for two Type R and two Type K). The I-V characteristic is displaced by 5 microamperes by typical roomlight conditions. This is roughly the same degree of excitation as a pulse of 1E8 rad sec-1 gives at its peak. The experiment suggests that, to characterize photovoltages on the RADFET, the use of "DC light" rather than pulsed radiation would greatly ease experimental difficulties. Holmes-Siedle and Cohen did some preliminary experiments with an optical-fibre illuminator and the magnitudes of voltages observed confirmed that useful results are likely if this line is pursued in future work. The effect of photocurrents will be proportional to the voltages generated across various elements of the RADFET, including the silicon substrate resistances. The substrate resistance values will be calculated in future work.

Finally, the possibility of producing "bucking currents" from external or built-in diodes in order to counteract the drain currents should be examined further.

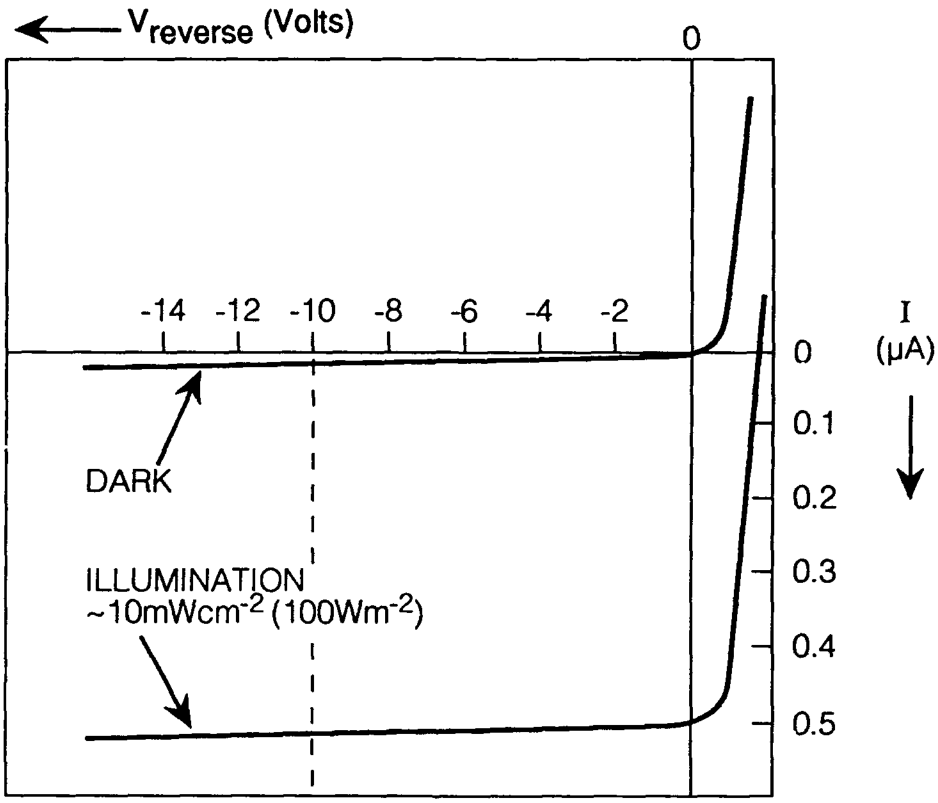


Fig. 5.4 Current-voltage curves for a small RADFET junction
(a) dark (b) under illumination of 10mW cm^{-2}

6. Radfet Deliveries

6.1 Prototypes

The delivery of production devices was preceded by two deliveries of prototypes to REM. Each lot was a mixture of chip types and package build. Samples were sent to Fort Monmouth for comment. Others were used for radiation testing, including the intensive series in June 1991.

6.2 Delivery 1AA

The delivery of this lot is described in REM Report AR-91-2R of July 1991). The production lot which included the US Army delivery 1AA was delivered to REM in June 1991. The makeup of delivery 1AA was discussed in detail with Dr. Kronenberg before the order for the lot makeup was placed in early May. Final advice from Dr. Kronenberg on encapsulant composition was received as promised - shortly after flash X-ray tests at Aberdeen, Maryland on the 14th May.

Table 6.1 shows the maximum, minimum and typical parameters for the production lot. Although this was a new encapsulation system (CC-3) the threshold voltages and stability values are seen as excellent. The number of rejects was larger than for the prototype batches in the CC-3 chip carrier but rejections for bad diodes were were on the whole fewer than for the ceramic DIL packages, rates running always lower than 10 percent.

Of the 290 ordered from the subcontractor, 278 were delivered, some "special filler" devices being rejected by the subcontractor on inspection. Table 6.2 shows the Item 1AA delivery sublots as agreed with Fort Monmouth. The largest single type in Item 1AA consists of 60 chips with the thicker oxide, encapsulated in the special encapsulant formulated by the US Army. Table 6.2 shows the composition of the Lot 1AA, devices selected from the above lot and delivered to CECOM in June 1991. The quantity was 120, not including prototype samples, which were supplied earlier.

6.3 Delivery 1AB and 1AC

These lots were delivered together as described in the delivery report REM-AR-92-1R. The makeup of this lot was decided by the US Army in late 1991. It was decided that items 1AB and 1AC should be of normal chip thickness. Half would be from existing wafers with oxide thickness values about 0.95 micrometres and half of value 1.24 micrometres (REM Specifications 502A and 504A). The CC-3 chip carrier was temporarily unavailable due to the closedown of a subcontractor and the Army agreed to take the delivery in Low-Gold Ceramic DIL package as in the previous contract. The lid type was grey ceramic and the seal was with silica loaded epoxy. 240 devices were delivered in April 1992, not including prototype samples supplied earlier.

Excluding prototypes, 450 devices were ordered from the subcontractor of which 240 were from Wafer 14 (0.95 μm) and 210 were from Wafer 19 (1.26 um). REM received devices on March 26

Table 6.1 Production Lot 1AA: Max, Min and Typical Parameters

Device Ser. and Type		Rcvd.	Meas.	THRESHOLD VOLTAGES * Rmin	Rmax (V)	Kmin	Kmax	DU R (mV)	K	REJ/TOT
501C-2-7	Sp	20	20	7.9	8.1	2.5	2.6	0.9	0.5	7/20
501c-8-4	Sp	20	19	5.9	6.1	2.6	2.9	0.7	0.2	2/20
501C-8-5	Tmp	20	0	-	-	-	-	-	-	-
502A-14-2	Sp	20	5	7.9	8.2	2.5	2.7	0.5	0.2	<10%
502A-14-3	Tmp	10	5	7.9	8.2	2.5	2.7	0.5	0.2	<10%
503A-18-1	Std	20	5	5.9	6.7	2.6	3.0	0.4	0.2	<10%
503A-18-2	Tmp	8	7	7.8	8.1	2.9	3.1	0.4	0.2	2/7
504A-19-2	Sp	74	74	8.8	10.2	2.9	3.2	0.9	0.5	14/74
504A-19-3	Std	38	39	8.8	9.6	2.9	3.1	0.9	0.5	3/38
504A-19-4	Tmp	49	49	8.8	9.6	2.9	3.2	0.9	0.5	2/49

Rcvd. = Number of RADFETs received

Meas. = Number measured to give above statistics

* Threshold voltages measured at 40 microamperes

Std = Standard Epoxy Cap

Sp. = Special filler added to Standard epoxy

Tmp = Temporary Cap

DU = Drift up in arithmetical value of V(T) between t = 2 sec. and t = 4 sec after applying "read" bias

TABLE 6.2 TECHNICAL DETAILS OF DELIVERY ITEM 0001AA, US ARMY

REM LOT NO.	QUANT.	WAFER NO.	CARRIER	PINS	ENCAPSULATION
		SUMC-			
502A - 14 - 2	5	P507U-14	CC-3	14	SPECIAL EPOXY
502A - 14 - 3	5	P507U-14	CC-3	14	TEMP. LID
503A - 18 - 1	5	" -18	CC-3	14	SPECIAL EPOXY
503A - 18 - 2	5	" -18	CC-3	14	TEMP. LID
504A - 19 - 2	60	" -19	CC-3	14	SPECIAL EPOXY
504A - 19 - 3	10	" -19	CC-3	14	STANDARD EPOXY
504A - 19 - 4	30	" -19	CC-3	14	TEMPORARY LID
TOTAL	120	DELIVERED JUNE 1991			

TABLE 6.3 TECHNICAL DETAILS OF DELIVERY ITEM 0001AB AND 1AC

REM LOT NO.	QUANT.	WAFER NO.	CARRIER	PINS	ENCAPSULATION
		SUMC-			
ARMY ITEM 0001AB					
502A - 14 - 5	120	P507U-14	LG-DIL	14	CERAM. LID
ARMY ITEM 0001AC					
502A - 19 - 6	120	P507U-14	LG-DIL	14	CERAM. LID
TOTAL	240	DELIVERED APRIL 1992			

1992. The PRODFET program was used to test the devices (see section 4). The yield of devices within specification was so high (over 98 percent) that after testing about 100, it was decided to test only one in every 5 devices. The readings are given in Table 4.1.

Table 6.3 shows that delivery item 1AB consisted of 120 of lot TOT502A-14-5 (0.95μm) on low-gold ceramic DIL packages with ceramic lids and delivery item 1AB consisted of 120 of lot TOT502A-14-5 (0.95μm) on low-gold ceramic DIL packages with ceramic lids.

7. Discussion

The RADFETs described in this final report were produced as a cost-sharing project with CECOM and the devices are a commercially viable product, being advertised under the specifications given in Appendix B. Devices with these specifications should be suitable for the engineering models of CECOM's AN/UDR-13 Pocket Radiac kit, which will be under study in late 1992. Although the present performance is adequate, several improvements would be desirable:

Lower threshold voltage - this is difficult to achieve but research into ion implantation methods could succeed

Better uniformity of threshold voltage - the wafer fabrication process used at present will not produce any higher uniformity; wafer probing and selection of a center cut of the devices would be a suitable way of increasing uniformity but of course, any selection process has a major impact on unit chip cost.

Lower radiation-induced drift - there is no known way of reducing the radiation-induced drift up after turnon. An improvement of performance (reduction of error induced by drift with time) can be implemented by the use of an intelligent reader which make measurements at precisely the same time after turnon.

Zero temperature coefficient (ZTC) - all FET designs have a ZTC point in their characteristic (e.g. about 160 microampere drive for TOT500). If not convenient to run always at this current, then it may be possible to redesign layout to achieve zero TC a lower drive current.

Reduction of enhancement of response under pulsed X-ray - it may be possible to reduce enhancement by changes in chip design but immediate measures consist of introducing a compensating diode and/or a stiffening capacitor in the external circuit. Internal chip design measures should also be pursued, however, it is necessary first to obtain a better physical picture of the effect and its dependence on chip parameters such as resistivity and source-body electrode relationships, effect of resistances in shorting media etc.

Other points emerging from the above work include the following:

Positive bias versus zero bias - the debate is not over; both methods have their advantages. It at least seems desirable to

limit any positive gate field applied to about 5 volts per micrometre (50,000 v. cm-1), so as to reduce stress and "bias annealing" of positive charge during the long inactive periods.

Sensitivity in the millrad region - REM observed that, in the zero-bias mode, responses in the 2 to 10 rad region seem very high. This may bring 1-rad sensitivity in the zero-bias mode within reach. This needs further research using shots of less than 1 rad, more precise temperature compensation and minimized oxide stress conditions. If it is desired to achieve sensitivity in the region of 0.1 rad, then further work using CVD to thicken the gate oxides is justified.

Photocurrents - the optimum configuration for accomodating the photocurrents generated in the RADFET under pulsed radiation has not yet been found but experiments with steady-state light could be an effective research technique.

Chip carrier and encapsulation - the benefits of a polymeric chip carrier have been demonstrated during this contract. A smaller carrier (SO-8 scale) would fit well with the desire to use surface mount technology in the Pocket Radiac. Attention should be paid to the formulation of the chip encapsulant (glob topping) so as to minimize directional sensitivity and energy dependence in the dosimeter.

8. Acknowledgements

The European Research Office of the US Army (Drs K. Steinbach and R. Seiders) is thanked for managing the contract and arranging facilities for testing at Aldermaston through their London office Dr. A. Cohen of Fort Monmouth is thanked for practical assistance during radiation testing in the UK in June 1991 and March 1992 and helpful liaison throughout the contract. Dr. S.Kronenberg, as Liaison Scientist gave valuable direction and useful scientific discussions over the course of the contract. Dr. E. Groeber, Chief, Sensor Systems Division and his colleagues Mr. Joe Nirschl, Chief, Radiac Development Branch, Project Leaders Ms Kim Black and Bekir Osman are thanked for hospitality, and direction of the project from Fort Monmouth, especially for initiating the request for the Flash X-Ray facility at AWE Aldermaston. AWE is thanked for provision of the facility at short notice and a shot-for-shot dosimetry service during the runs.

9. Conclusions

This second contract to supply RADFETs to the US Army again included some evolution of device design and dosimetric methods over and above the supply of commercial parts. The aims of REM are to improve chip performance, chip carrier design, dosimetric probe design and other parts of RADFET dosimeter methodology. The present contract constitutes a scientific collaboration during which new concepts and methods can be tried out alongside commercial supply of a dosimeter product. During this period a thicker oxide has been produced and a completely original chip carrier has been designed and proved. The response of the thicker oxide is significantly higher than previous devices and stability stays about the same. The thicker oxide value (1.26 micrometres) should be considered seriously for upcoming equipment projects. The chip carrier made possible some interesting new absorber geometries around the chip.

Direct research collaboration with CECOM staff at Fort Monmouth gave rise to a method of adjusting the radiation scattering power of the encapsulating package and some concepts for photocurrent compensation. REM, CECOM and the US Army's London Research Office (UKRDSG) were guests of the UK Atomic Weapons Establishment for a pulsed test at Aldermaston, England.

Further tests to iron out technical questions and methodology are necessary, as mentioned in the discussion section. These would fit naturally into a chip research project proceeding in parallel with the engineering phase of prototype equipment. The technical topics include device encapsulation, the choice of zero-bias or biassed mode and the optimum configuration for accomodating the photocurrents generated in a RADFET under pulsed radiation.

Despite these open questions, the recent work has increased confidence that RADFET dosimetry is a strong candidate for future tactical dosimetry equipment.

10. References

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APPENDIX A

PRINTOUTS OF ELECTRICAL MEASUREMENTS

MADE WITH THE AID OF THE

(REM PROPRIETARY) PRODFET AND STABFET PROGRAMS

Data as presented by the programs on screen

KEY TO TABLES

"Q1 2secs" is the threshold voltage reading for RADFET Q1 2 sec after a "read" current of 40 microamps is switched to FET no. Q1

"4sec" is the change in the reading on Q1 2 seconds later

"90uA" is the change in the reading on Q1 after raising the read current to 90 microamps (yields a measure of the gain)

A. Holmes-Siedle, REM

24/5/92 arfr-1a

A1. Drift measurement on unirradiated RADFET FROM 0.5 TO 1000 seconds, illustrating logarithmic time dependence and stability of about 0.3 mV per twofold time interval. d(ox) = 1.26 um

Time	Voltage	Drift (2s)	Drift (10s)	Time	Voltage	Drift (2s)	Drift (10S
.5	10.1234	-0.20	-0.80	60	10.1248	1.2	0.6
1	10.1231	-0.50	-1.10	80	10.1249	1.3	0.7
1.5	10.1233	-0.30	-0.90	100	10.1249	1.3	0.7
2	10.1236		-0.60	200	10.1257	2.1	1.5
3	10.1237	0.1	-0.50	400	10.1263	2.7	2.1
4	10.1239	0.3	-0.30	600	10.1269	3.3	2.7
5	10.1239	0.3	-0.30	800	10.1274	3.8	3.2
6	10.1240	0.4	-0.20	1000	10.1271	3.5	2.9
8	10.1241	0.5	-0.10	2000			
10	10.1242	0.6		5000			
12	10.1243	0.7	0.1	10000			
14	10.1244	0.8	0.2	20000			
16	10.1244	0.8	0.2	50000			
18	10.1244	0.8	0.2	86400			
20	10.1245	0.9	0.3	100000			
40	10.1247	1.1	0.5	360000			

2-4s Drift= 0.3   10-20s Drift= 0.3

A2. Drift measurement on irradiated RADFET FROM 0.5 TO 20,000 seconds, illustrating drift of about 8 mV per twofold time interval. Dose 3000 rad, zero irradiation bias, d(ox) = 1.26 um

File: fadef4.STB   11 June 1992
Device: TOT501C-7-4B #1 Q4Next measurement: 67972   11:34:42

Time	Voltage	Drift (2s)	Drift (10s)	Time	Voltage	Drift (2s)	Drift (10S)
.5	8.7466	-25.70	-43.90	60	8.8073	35.0	16.8
1	8.7605	-11.80	-30.00	80	8.8104	38.1	19.9
1.5	8.7677	-4.60	-22.80	100	8.8127	40.4	22.2
2	8.7723		-18.20	200	8.8196	47.3	29.1
3	8.7768	4.5	-13.70	400	8.8274	55.1	36.9
4	8.7802	7.9	-10.30	600	8.8324	60.1	41.9
5	8.7834	11.1	-7.10	800	8.8367	64.4	46.2
6	8.7858	13.5	-4.70	1000	8.8397	67.4	49.2
8	8.7887	16.4	-1.80	2000	8.8496	77.3	59.1
10	8.7905	18.2		5000	8.8636	91.3	73.1
12	8.7925	20.2	2.0	10000	8.8770	104.7	86.5
14	8.7940	21.7	3.5	20000	8.8953	123.0	104.8
16	8.7963	24.0	5.8	50000			
18	8.7976	25.3	7.1	86400			
20	8.7988	26.5	8.3	100000			
40	8.8037	31.4	13.2	360000			

2-4s Drift= 7.9   10-20s Drift= 8.3

Typical unirradiated samples from Wafer 19 ; PRODFET routine

4 March 1992 12:44:23

File : EV19CER1.PRD
Batch : TOT0504A-19-5
Device: 1

	2 secs	4 secs	90 mA	Drift Up	Difference
Q4	10.1424	10.1428	10.6825	0.4	540.1
Q1	10.1338	10.1343	10.6736	0.5	539.8
Q2	3.2168	3.2164	3.4670	-0.4	250.2
Q3	3.1508	3.1514	3.4030	0.6	252.2

4 March 1992 12:48:41

File : EV19CER1.PRD
Batch : TOT0504A-19-5
Device: 2

	2 secs	4 secs	90 mA	Drift Up	Difference
Q4	10.0863	10.0865	10.6203	0.2	534.0
Q1	10.0374	10.0377	10.5704	0.3	533.0
Q2	3.2080	3.2081	3.4537	0.1	245.7
Q3	1.3358	1.3431	1.6615	7.3	325.7

Typical unirradiated samples from Wafer 14 ; PRODFET routine

4 March 1992 12:00:02

File : ev14tie1.PRD
Batch : TOT-502A-14-2
Device: 2

	2 secs	4 secs	90 mA	Drift Up	Difference
Q4	8.0692	8.0695	8.6431	0.3	573.9
Q1	8.0379	8.0384	8.6089	0.5	571.0
Q2	2.5910	2.5871	2.8645	-3.9	273.5
Q3	2.5921	2.5921	2.8702	0.0	278.1

4 March 1992 12:05:12

File : ev14tie1.PRD
Batch : TOT-502A-14-2
Device: 3

	2 secs	4 secs	90 mA	Drift Up	Difference
Q4	8.1844	8.1849	8.7716	0.5	587.2
Q1	8.1856	8.1863	8.7733	0.7	587.7
Q2	2.6157	2.6157	2.8987	0.0	283.0
Q3	2.6118	2.6115	2.8944	-0.3	282.6

Appendix B

Specification No. REM TOSP-92-1(Issue 1)

SPECIFICATION FOR

THE RADFET DOSIMETER TYPE TOT500 (14 PIN)

DATE: 22ND JUNE 1992

RADIATION EXPERIMENTS AND MONITORS (R.E.M.)
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EYNSHAM
OXFORD OX8 1PD
ENGLAND
PHONE : +44-865-880050

tosp-92-1

RADIATION EXPERIMENTS AND MONITORS (REM), OXFORD, ENGLAND

SPECIFICATION FOR THE RADFET DOSIMETER TYPE TOT501 (14 -PIN)

1. GENERAL

The RADFET is an integrating dosimeter, formed from an MOS structure which measures dose (rad or Gy(Si)) by the space-charge buildup principle. The multiple RADFET elements can be used as discrete dosimeters or jointly for temperature compensation and other balance circuits.

REM TYPE TOT500 CHIP : Die dimensions 1.0 x 1.0 mm.
Contains 4 FETs:
two Type R ("RAD dose level"),
two Type K ("KILORAD dose level").
Gate oxides are specially processed to optimize long-term charge trapping. Thickness, t(ox) of gate oxides: Type R : over 0.5 micrometres; Type K: under 0.26 micrometres. Type is specified by Recipe No.(e.g. 501C); Wafer number; lot number - giving lot numbers such as "TOT501C-2-3".

2.ELECTRICAL SPECIFICATIIONS

ELECTRICAL PARAMETERS : RADFETs are enhancement pMOS transistors. I-V characteristics resemble those of pMOS switching FETs. Dosimetry involves tracking threshold voltage, V(T), at 10 to 250 uA. For values of V(T) see Table. The shift of V(T) given by a given amount of charge trapping is dependent on the thickness of the gate oxide. The initial threshold voltage values for the FETs and some I(D)-V(G) characteristics are specified in data sheets.

STABILITY - GENERAL: In unirradiated RADFETS, drift of V(T) with time can be caused by interface states or ionic motion. Larger drift effects are observed after irradiation. The value of "du 10/20s", is the increase in the arithmetical value of V(T) between time values of 10 and 20 seconds after turnon of the V(T) tracker at a drain current value of 40 microamperes. Low du values indicate good stability. Values specified in data sheets. Irradiation increases the drift up strongly. e.g. a drift of 0.5 mV may be produced by exposure to 50 rad(Si) of gamma rays at V(I)=0; the same dose produces a permanent radiation-induced V(T) shift of over 50 mV (i.e. 100 times larger).

STABILITY SPECIFICATION: Grade "Ae": the threshold voltage shall drift up by not more than 0.60V over the time period between 10 and 20 seconds after the constant current source of the reader is applied to the source (expressed as "du 10/20s = 0.60 mV"). "Ag": the above test shall produce drift up of less than 1.0 mV .

4. RADIATION RESPONSE SPECIFICATIONS

The shift in threshold voltage, delta V(T), can be calibrated to correspond to a unique exposure dose, given controlled field conditions in the gate oxide. Both linear and non-linear modes are are used, depending on availability of bias. The two modes are illustrated in growth curves forming part of the data sheets. Drifts after irradiation, fade and reverse fade, can also occur.

5. PACKAGES AND PINOUTS

HEADER : The standard type is a 14-pin dual-in-line ceramic body,7 x 18 x 2mm; with side brazed pins, 2.54 mm spacing. The die bond is silica-filled epoxy. The wire bonds are Aluminium. Alternative special designs of header have lower gold content, including a version with polymeric body and surface mount leads.

The standard type is gold plated kovar with a hermetic solder seal produced in an inert atmosphere. For the low-gold styles, the choice is epoxy-bonded ceramic or black epoxy glob top. In The hermetic version meets MIL STD 883 with respect to bond strength and dewpoint.

PINOUT: Normal 14-pin version has four devices wired up;

Small 8-pin device has two or three devices wired up;

Miniature probes available

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DATA SHEET TOT501/1: PARAMETER SPECIFICATIONS FOR RADFET TYPE 501

	MIN.	TYP.	MAX.	UNITS	CONDITION
OXIDE THICKNESS					
d(ox) ; R	0.82	0.86	0.87	um	
d(ox) ; K	0.25	0.26	0.26	um	
THRESHOLD VOLTAGE					
V(T) ; R	-6.0	-6.8	-9.0	V	40uA
V(T) ; K	-2.5	-3.0	-4.0	V	40uA
GAMMA RAY RESPONSIVITY (10 rad(Si) or 0.1 Gy(Si))					
irradiation bias on gate V(I) = +20V					
r(+) ; R	....	99	....	mV	exposed to 10 rad under +20V
r(+) ; K	....	6.0	....	mV	
irradiation bias on gate V(I) = 0					
r(0) ; R	....	11	....	mV	exposed to 10 rad under 0V
r(0) ; K	....	2.0	....	mV	
STABILITY RATING					
	Ae'	Ae	Ag		
du : R	0.35	0.50	1.00	mV	10 - 20 sec. in "Read" Mode
du ; K	0.2	0.3	0.4	mV	

Oxide of wafer lot uniform to 0.1 percent ; V(T) = gate voltage for I(D) = 40uA ; r(+) = radiation response with +20V on gate ; r(0) = response with all leads shorted; du 10/20 = drift up i.e. difference of V(T) at t=10 and 20 seconds after switching to "read" mode ; A = acceptable e=excellent g=good

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PRELIMINARY SPECIFICATIONS FOR EXPERIMENTAL RADFET TYPE 504

		MIN.	TYP.	MAX.	UNITS	CONDITION
OXIDE THICKNESS						
d(ox)	R	—	1.26	—	um	
d(ox)	K	—	0.13	—	um	
THRESHOLD VOLTAGE						
V(T)	R	-9.0	-9.6	-9.9	V	40μA
V(T)	K	-2.8	-3.1	-3.4	V	40μA
GAMMA RAY RESPONSIVITY (10 rad(Si) or 0.1 Gy(Si))						
irradiation bias on gate V(I) = +20V						
r(+)	R		160		mV/10r	exposed to 10 rad
r(+)	K		6		mV/10r	under +20V gate bias
irradiation bias on gate V(I) = 0						
r(0)	R		20		mV/10r	exposed to 10 rad
r(0)	K		0.5		mV/10r	under zero gate bias
STABILITY RATING						
		Ae'	Ae	Ag		
du	R	0.30	0.60	1.00	mV	10 - 20sec. in
du	K	0.10	0.20	0.30	mV	"Read" Mode

Oxide thickness of wafer lot uniform to 0.1 percent ; V(T) = gate voltage, I(D) = 40uA ; r(+) = radiation response with +20V on gate ; r(0) = response with all leads shorted; du 10/20 = drift up i.e. difference of V(T) at t=10 and 20 seconds after switching to "read" mode ; A = acceptable e=excellent g=good

RADFET CHARACTERISTICS

The RADFET is an integrating dosimeter for ionising radiation. Dose is determined by the measurement of long-lived trapped charge, generated by photons and particles in a silicon dioxide layer grown on silicon. The principle and construction of the RADFET and designs of reader circuits for various applications are given in the bibliography.

Several SPACE RADIATION MONITORS are already in orbit. Several armed services are pursuing RADFET dosimeters for personnel protection. In RADIATION EFFECTS TESTING of electronic devices, the RADFET has been used for integrating the ionising dose in the radiation beam. In NUCLEAR FACILITIES, a RADFET damage monitor system will be fitted to Class E1 instruments, robots, area monitoring arrays and cavity dosimeters. In MEDICINE, use of the RADFET as a patient probe, a beam checker and an immunotherapy probe has been proven.

The dynamic range is very large, being nine orders of magnitude from 0.1 rad (1 mGy) to 100 megarad (1 MGy) with potential for extension at both ends of the scale.

ADVANTAGES OF THE RADFET METHOD OF DOSIMETRY

The advantages of the RADFET system include:

- immediate read-out without destroying the data
- Extremely small, rugged sensor chip
- very low or zero power drain
- the sensor chip can operate on a long cable or on a retrofittable sub-board
- technology suitable for connection to a microprocessor

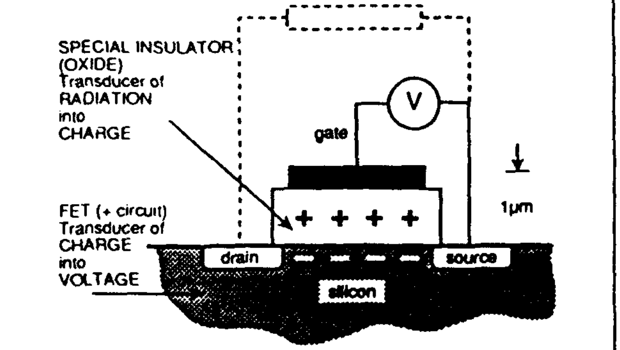

Fig. 1 Principle of the RADFET chip

- very wide dynamic range for integrated dose range measured
- little fading
- RADFETs exhibit responses to gamma-rays, heavy ions, x-rays hard and soft, VUV, electrons, protons and neutrons.

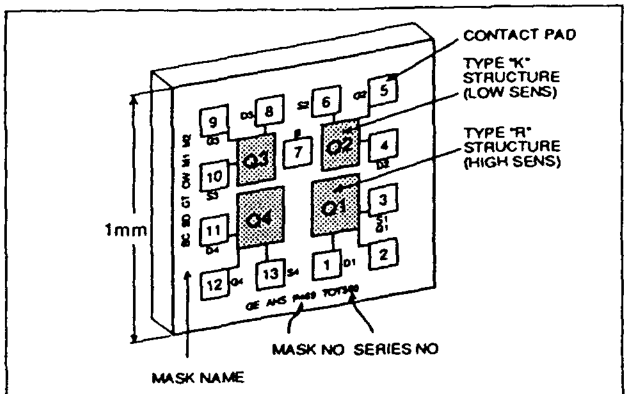

Fig. 2 Layout of the RADFET 500 chip

THE REM TYPE 500 RADFET

The RADFETs are based on Al-gate p-channel MOS technology, very thin metal gates and high drive capability.

One pair of the FETs shown, called Type 'R', carries the THICK gate insulator. This makes it extra sensitive to radiation. The thickness is about ten times that normally used for MOSFET gate oxides in integrated circuits. This design gives a dosimeter suitable for measuring low doses ('R' stands for 'rad' doses). The other pair, Type 'K', carries an oxide which is relatively THIN but still over twice as thick as those commonly used. Type 'K' is suitable for moderate to high doses ('K' stands for 'kilorad' doses). Each type can be used in different modes, which broadens the dynamic range. The four devices can be operated as separate sensors or can be cascaded to provide enhanced response. The pinout and circuit of Type 500 is shown here. The active volume of the sensitive insulator is 1E-5 cubic mm; The dimensions of the 4 - RADFET die are only 1mm x 1mm.

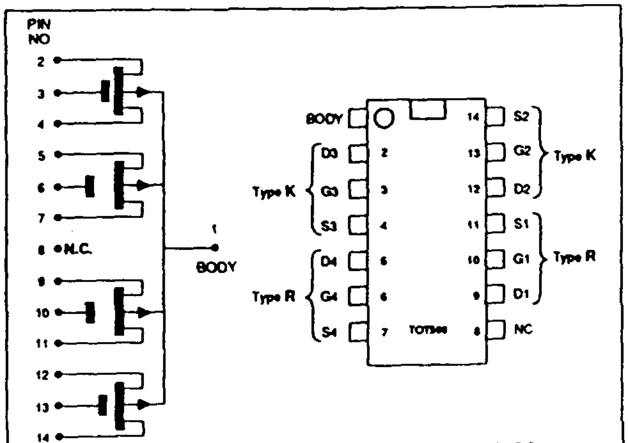

Fig. 3 Pinout diagram of RADFET TOT500

The small size of the RADFET has demonstrated several advantages:

- a RADFET chip has been mounted in a very small catheter

- an array of RADFETS gives a high-resolution dose image
- the yield per wafer in commercial processing is high, making possible a low cost sensor.

AVAILABILITY OF RADFET CHIPS

REM has WAFER STOCK, made in the UK, of the type TOT501 RADFET, sufficient to make over 10,000 devices. Quantities of hundreds can be sawn and assembled in conventional packages (TO-18)

AVAILABILITY OF SENSOR CONTROL ELECTRONICS

Two firms have developed electronic systems to apply bias and to measure the threshold voltage shifts of the RADFET, which are then translated into dose. The European Space Agency has adopted one of these systems as the ESA Modular Dosimeter, which can be attached to any spacecraft with a standard telemetry and command system. REM can put potential users in touch with these firms and, as appropriate, with other researchers who have built non-commercial systems.

PERFORMANCE SPECIFICATION

A full RADFET performance specification (REM-90-TOT-505-3) has been developed in co-operation with a major user of radiation sensors in the USA. RADFETs are being delivered to this user on a regular basis. The RADFET structure is approved for spacecraft use. The performance of the RADFET is being developed by REM to meet various applications including medical treatment, millirad accident dosimetry, reactor dosimetry and megarad radiation processing.

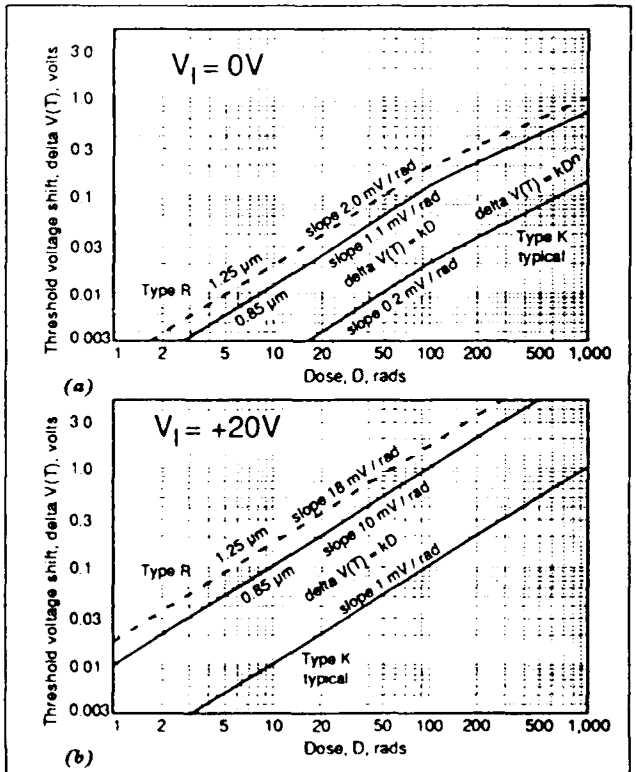

Fig 4 Nominal response of the TOT501 RADFET for two bias modes
(a) zero bias during irradiation (V_I=0)
(b) positive bias during irradiation (V_I=+20V)

APPLICATIONS OF RADFET DOSIMETRY

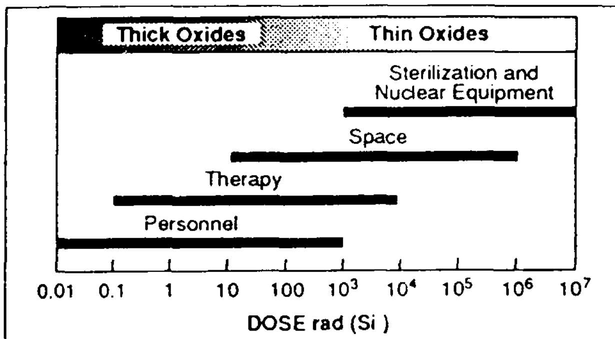

Fig. 5 Applications and dosage ranges

Nuclear Industry

- small, inexpensive, low-power dosimeter system to read environmental doses in 'hot' areas of a reactor building or isotope storage building
- dosimeter to signal the need for the replacement of electronic equipment in CLASS 1E INSTRUMENTS
- calibration in the radiation testing of ELECTRONICS

Radiation Beam Mapping

- beam quality control for processing and therapy
- radiation hardness testing
- semiconductor photolithography
- industrial radiography
- short-wavelength UV lamps

End of Life Monitoring in Space

- spacecraft equipment has to be replaced at some specified dose level. An "ESA Modular Dosimeter" using REM RADFETs has been designed and flown (Holmes-Siedle 1990).

Therapy Systems

- A miniature RADFET probe and tracker have been used in cancer treatment by Hughes and co-workers (1988)
- Miniature patient monitors and tumour probes using the REM TOT500 chip are reported by Gladstone, Chin, Holmes-Siedle and Humm (1991)

Environmental and Personnel Badges

- REM TOT501 RADFETs are under test as "Accident Dosimeters"

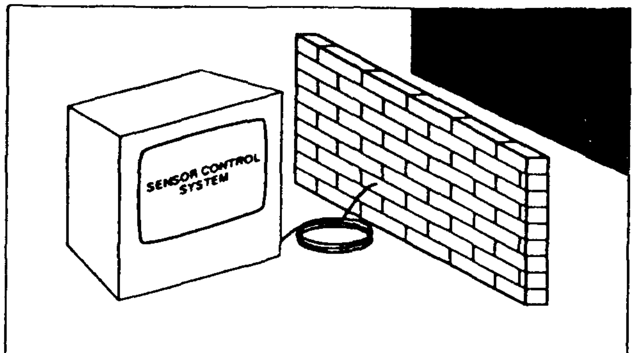

Fig. 6 REM devices were used in a fusion experment in the USA

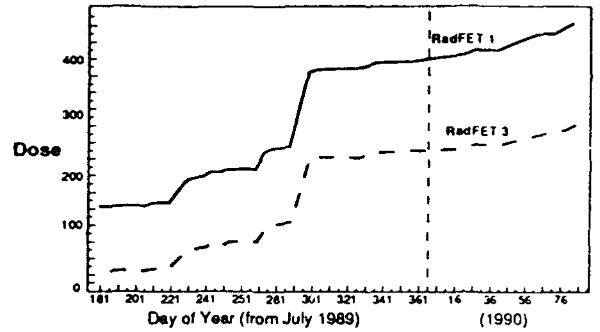

Fig. 8 REM devices detected three major solar flares in 1989

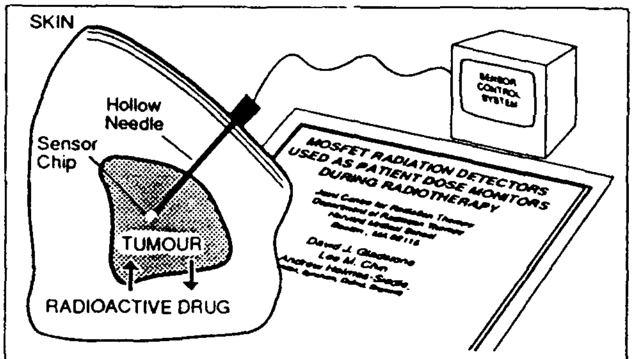

Fig. 7 REM devices were used to measure doses during radiotherapy

PRICE GUIDE

A typical RADFET price is composed of various elements of added value. Chip - 20%; package - 30%; assembly - 20%; testing - 30%. Prices for quantities from 5 to 10,000 units can be quoted. As of 1991 quantities of devices in low cost packages with minimum testing have a unit price in the region of £20 ($33, 190FF). Electronic reader systems vary from £2,000 to £5,000.

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